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Salinity Changes in Pontchartrain Basin Estuary Resulting from Bonnet Carré Freshwater Diversion

Numerical Model Investigation

by William H. McAnally, R. C. Berger

Prepared for U.S. Army Engineer District, New Orleans

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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Prepared for U.S. Army Engineer District, New Orleans
P.O. Box 60267
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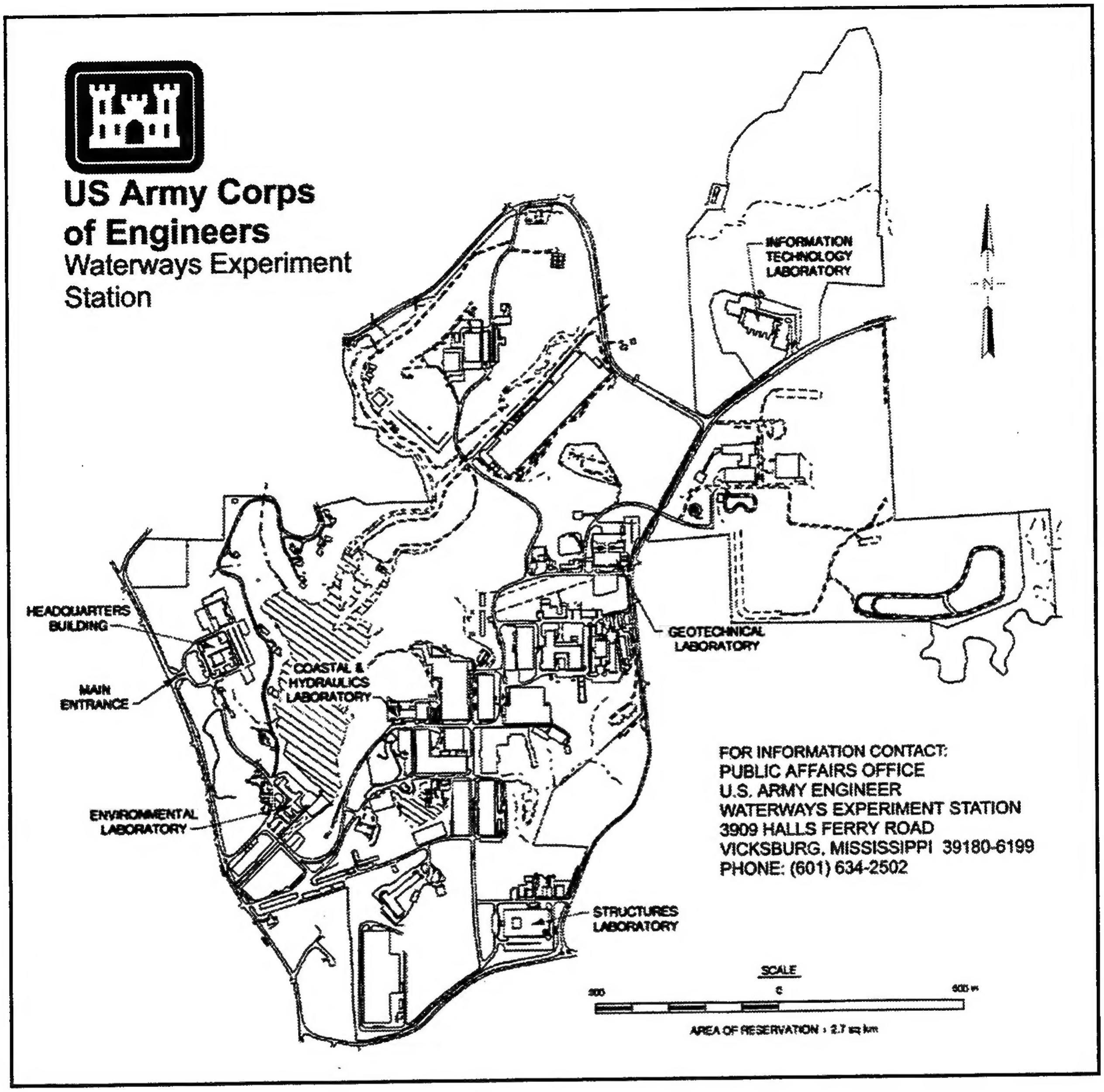

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Preface

The work described here was performed from April 1995 through July 1996 at the U.S. Army Engineer Waterways Experiment Station (WES) with funding provided by the U. S. Army Engineer District, New Orleans (LMN). LMN liaison was provided by Messrs. Jack Fredine, Bill Hicks, Dom Elguezabal, and Burnell Thibodeaux.

Personnel of the WES Hydraulics Laboratory, Waterways and Estuaries Division, performed this investigation under the general direction of Mr. Richard A. Sager, Acting Director of the Hydraulics Laboratory, and under the direct supervision of Mr. William H. McAnally, Chief, Waterways and Estuaries Division. Dr. R. C. Berger, principal investigator, was assisted by Messrs. McAnally, Andrew Berner, Jay Hardy, and Ben Brown and Ms. Cassandra Gaines. Mr. Joseph V. Letter, Dr. Gregory H. Nail, and Mr. Robert F. Athow provided valuable assistance to the effort. This report was written by Mr. McAnally and Dr. Berger.

The excellent advice of Messrs. Thibodeaux and Fredine; the Bonnet Carré Interagency Technical Team; and the U. S. Army Corps of Engineers Committee on Tidal Hydraulics, particularly Dr. Donald W. Pritchard, is gratefully acknowledged. The interagency Technical Team included Messrs. Ken Kirkpatrick, Wes McQuiddy, and Oscar Ramirez, U.S. Environmental Protection Agency; Drs. John Day and Joe Suhayda, Louisiana State University; Dr. Steve Gorin and Mr. Neil Armingeon, Lake Pontchartrain Basin Foundation; Mr. Tom Van Devender, Mississippi Department of Marine Resources; Mr. Phil Bowman, Louisiana Department of Wildlife and Fisheries; Dr. Bill Good and Mr. Carroll Clark, Louisiana Department of Natural Resources; and Messrs. Fredine and McAnally, U. S. Army Corps of Engineers.

Director of WES during preparation and publication of this report was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
square feet	0.09290304	square meters

Summary

Numerical model experiments were performed to predict salinity changes that will occur in the Lake Pontchartrain basin estuary, Louisiana and Mississippi, as a result of proposed Mississippi River freshwater diversions through the Bonnet Carré spillway near New Orleans. One purpose of the diversion is to reduce salinities in the Biloxi Marshes by 2 to 8 parts per thousand (ppt) in order to improve oyster productivity. A range of monthly salinities has been identified as the desired product of the project. Those salinities, called the Chatry salinities in this report, consist of a narrow band of "optimum" salinities and a somewhat wider band of "range limits."

A time-varying, three-dimensional numerical model of the estuary was constructed using the U.S. Army Corps of Engineers TABS-MD modeling system. The modeled area included Lakes Maurepas, Pontchartrain, and Borgne, Biloxi Marshes, and a portion of Chandeleur Sound plus connecting waterways of Mississippi River-Gulf Outlet (MRGO), Inner Harbor Navigation Canal, Gulf Intracoastal Waterway, Chef Menteur, and The Rigolets. All major tributary freshwater flows were simulated, as were tides at the Gulf of Mexico boundary and winds. The model computed instantaneous water levels and current velocities and salinities in three spatial dimensions throughout the area modeled. The model was verified to satisfactorily reproduce hydrodynamic behavior observed in the natural system in 1982 and 1994.

Four conditions were modeled for April through August of a typical year: a Base condition with no diversion, Plan RT with freshwater diversions up to 20,000 cfs, Plan MBP5 with freshwater diversions up to 8,500 cfs, and Plan LBC1, with no freshwater diversions but with the connections between the MRGO and Lake Borgne closed.

The numerical model results were used to construct a simple regression equation that relates Biloxi Marsh salinities at a point to freshwater flows from the natural tributaries plus the diversions. The equation was then used to develop other diversion schedules that offered various salinity reduction scenarios.

The following conclusions and recommendations are drawn from the work:

a. The estuary responds very slowly to changes in freshwater inflow to Lake Pontchartrain. For example, in the Biloxi Marshes salinity effects are noticeable within 30 days of a change in flow, but the peak effect occurs at about 60 days and a noticeable residual effect remains at 120 days.

b. The MRGO is a significant contributor to the salinity regime in the Lake Pontchartrain to Biloxi Marshes area, primarily via MRGO connections to Lake Borgne.

c. A Bonnet Carré structure discharge capacity of about 30,000 cfs is required to achieve the desired spring salinity of about 6 ppt about every other year at Line 2, a location in the Biloxi Marshes identified as the target location in the General Design Memorandum (GDM). However, any year in which that low salinity is achieved (either by diversion or natural freshening) will be fresher than desired in the subsequent 2 months because of the slow response time of the system.

d. The plans considered here will reduce salinities at Line 2 in the Biloxi Marshes for a typical year (50 percent exceedance flows). Specifically, compared to the Base, or no diversion, condition, the plans had the following effects on salinities at about the center of Line 2:

(1) Plan RT (up to 20,000 cfs) reduced salinities up to 4.2 ppt during April-August. It reduced salinities to Chatry optimum values or less 10 months out of 12.

(2) Plan MBP5 (up to 8,500 cfs) reduced salinities up to 3.4 ppt during April-August. It reduced salinities to Chatry optimum values or less 9 months out of 12.

(3) Plan LBC1 (closure of Lake Borgne-MRGO connections) reduced salinities up to about 2 ppt during April-August.

e. Other potential diversion schedules can be devised and salinity reduction approximated by the simple equation developed in this report without additional model experimentation in order to balance achievement of salinity goals with other criteria. However, any plan devised by that method should be subjected to model experimentation before design is complete and before an operational plan is designed.

f. Control of salt flux up MRGO and through the outlets can contribute significantly to achieving Biloxi Marsh salinity goals. Possible control methods are discussed in Chapter 5 of this report. By extension, it may be possible to combine MRGO salt contributions with smaller diversions (e.g., MBPJ) to approach target salinities at Line 2.

g. The basin response conclusions in item *d* imply that a Bonnet Carré diversion schedule must be statistically based. Before construction of a

project, the plans reported here must be replaced with a diversion operational plan that takes into account antecedent conditions and a stochastic forecast of future tributary inflows. Such an operational plan will produce some years fresher than desired and some years saltier than desired, as described in the GDM. Chapter 5 of this report suggests an approach for developing such an operational plan.

1 Introduction

Background

Project description

The Bonnet Carré Freshwater Diversion project will divert Mississippi River water through the existing Bonnet Carré spillway near New Orleans, LA, to reduce salinities in the Mississippi and Louisiana estuaries of the Lake Pontchartrain Basin (Figure 1). The project, authorized by the Water Resources Development Act of 1988, is sponsored by the U. S. Army Engineer District, New Orleans, Mississippi State Department of Marine Resources, and Louisiana State Department of Natural Resources. Its purpose is to provide environmental and economic benefits to the basin.

The diversion project design includes a structure and channel in the Bonnet Carré spillway that will divert river water into the southwestern corner of Lake Pontchartrain. The project is described in detail in a general design memorandum (U.S. Army Engineer District (USAED), New Orleans, 1990) and a feasibility study report (U.S. Army Engineer District, New Orleans, 1984).

The project was designed to produce salinities in the Biloxi Marshes that would be beneficial for oyster production, achieving specified target salinities on average every other year (i.e., 50 percent of the time.) The specified target salinities were those defined as optimal by Chatry, Dugas, and Easley (1983) and are shown in Table 1. The Chatry salinities consist of an optimum range and range limits. The optimum range represents plus and minus one standard deviation about the monthly mean observed salinities that correlated with eight subsequent years of good oyster production in the Breton Sound estuary during 1971-1981. The range limits are the range of observed monthly average salinities that correlated with those 8 years.

Figure 1 shows the area where the optimum salinities were intended to occur (U.S. Army Engineer District, New Orleans, 1990). Other projected benefits included marsh protection and restoration in the basin.

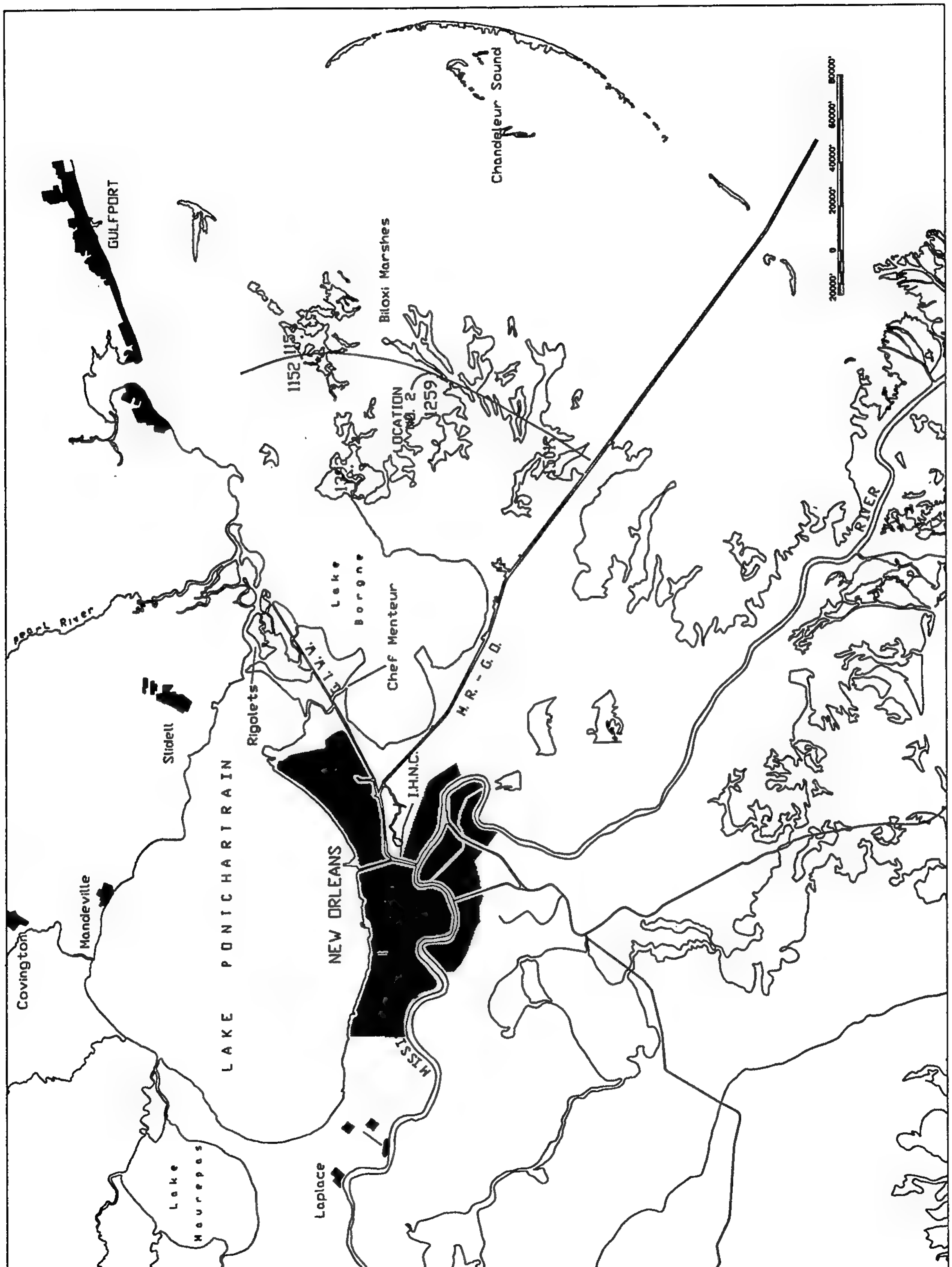

Figure 1. Vicinity map

Table 1
Salinity Targets for the Biloxi Marshes, ppt

Month	Chatry Average Target	Mean Ambient Salinity	Needed Reduction	Chatry Optimum Limits		Chatry Range Limits	
				Low	High	Lowest	Highest
Jan	16.5	19.5	3.0	15.5	17.5	15.0	19.0
Feb	14.5	16.5	2.0	13.5	15.0	11.0	17.0
Mar	11.5	15.0	3.5	10.5	12.5	7.5	15.0
Apr	8.0	14.0	6.0	7.0	9.5	2.0	13.0
May	7.0	15.0	8.0	6.0	8.0	4.5	11.5
Jun	12.5	17.0	4.5	12.0	13.5	9.0	16.0
Jul	13.0	20.5	7.5	12.5	13.0	10.5	15.0
Aug	16.0	22.0	6.0	15.0	16.5	13.0	17.5
Sep	17.0	23.0	6.0	16.0	18.0	15.0	24.0
Oct	17.0	24.0	7.0	16.0	18.0	13.0	18.5
Nov	16.0	24.0	8.0	15.0	17.0	11.5	18.5
Dec	16.0	23.0	7.0	15.5	16.5	13.0	17.0

Note: Salinity targets estimated to nearest 0.5 ppt from graphical display in Chatry et al. (1983). Ambient salinities rounded to 0.5 ppt using Pankow et al. (1989) Equation 10a and 50 percent exceedance discharges from tributaries.

The Bonnet Carré diversion structure was designed with a maximum gravity flow capacity of about 34,000 cfs[1] for a 50 percent probable Mississippi River stage for April and about 8,000 cfs in September and October. Table 2 lists the design capacity for each month assuming a 50 percent river stage and mean water level in Lake Pontchartrain. The maximum design flows were selected based on a regression analysis relating observed salinities in the Biloxi Marshes to tributary river flows over several years (Pankow et al. 1989; USAED, New Orleans, 1984) and then applied to 50 percent exceedance flows for those tributaries. The maximum required flow according to those analyses was about 30,000 cfs, so the structure was designed accordingly. The maximum flows of Table 2 are based on an HEC-2 analysis of flow losses through the design structure and channelized flow through the floodway to Lake Pontchartrain (USAED, New Orleans, 1990). A different structure or floodway conveyance design may increase or decrease those design capacities.

[1]A table of factors for converting non-SI units of measurement to SI units is found on page vii.

Table 2 Monthly 50 Percent Exceedance Discharges, cfs			
Month	Lakes Pontchartrain and Maurepas	Pearl River	Diversion Structure Capacity
Jan	4,257	9,602	22,400
Feb	5,281	18,060	27,400
Mar	5,481	19,120	32,400
Apr	4,625	15,510	34,468
May	2,914	10,090	32,300
Jun	1,709	4,178	24,950
Jul	1,715	3,522	16,800
Aug	1,501	2,792	10,700
Sep	1,387	2,388	7,600
Oct	1,187	2,047	8,150
Nov	1,285	2,651	8,600
Dec	3,095	5,339	12,500

Technical Team review

Concerns expressed by some organizations and individuals about the project's effects on Lake Pontchartrain led to an interagency reevaluation of the project during 1994-96. In a November 1994 statement, an Interagency Technical Team made recommendations on the following three items:[1]

"Item 1 -- Feasibility of overflowing all or part of the diverted water through the wetlands.

"*a.* Using the spillway and adjacent wetlands is scientifically feasible for diverting 2,000 - 6,000 cfs of Mississippi River water. Retention time would be about one day, and about 20 to 60 percent of the nutrients and sediments would be removed.

"*b.* Qualifications to the above statement:

(1) Excess loading reduces the removal efficiency of overland flow.

(2) Systems used for estimates of nutrient removal were somewhat similar, but also had significant differences. Site specific data was lacking.

[1] From minutes of Interagency Technical Team, November 1994.

(3) Diversions through adjacent wetlands will probably require modifications to the design of this project and other Corps projects nearby, like the St. Charles Hurricane Protection Levee.

(4) Diversions through adjacent wetlands will require cooperation and coordination with owners of these wetlands.

"*c.* The Corps should pursue maximizing that portion of the diversion that is feasible to put into the wetlands, limited by physical/biological constraints.

"d. Nutrients in the Lake

(1) To minimize risk of eutrophic impact, the N/P ratio of water reaching the lake should be 10 or above and not exceed specific concentrations.

(2) The lake bottom can also remove some nutrients.

"Item 2 -- Guidelines for and operational schedule to ensure the Ecological Protection and Enhancement of the upper Lake Pontchartrain Basin.

"*a.* Salinities in the target area should not exceed 20 ppt more than one month in the period from March to October, and should be maintained near or below 15. Review of flow scenarios investigated by Hoese and Melancon divided them into tiers.

"*b.* Circulation and salinity analysis by McAnally suggested that target salinities can be substantially achieved with flows significantly below the GDM by a 4 month freshening effect, and the 'steering the Pearl' concept.

"*c.* The Technical Team recommends that:

(1) Design modifications be initiated to divert the maximum amount possible through the wetlands (current estimate, 6,000 cfs)

(2) A 'comprehensive' monitoring plan for the project be developed.

(3) Any excess spoil material from the spillway should be used to create wetlands in the spillway or along the shore of Lake Pontchartrain, or in the La Branche marsh which ever is most cost and ecologically effective.

"*d.* An intensive long range monitoring system will be used to prevent damage to the wetlands, the Lake, and the fisheries in the Lake. Use of the data developed from monitoring to fill the information gaps that were apparent from the reanalysis process. This much needed information to be used to prevent damage to the Basin ecosystem, to

improve environmental conditions in this and other Basins and to enhance fin and shellfish production. This should be a combined effort of agencies, environmental groups and the academic community.

"*e.* A monitoring program will be fashioned for the Lake Pontchartrain Basin (to include Lakes Pontchartrain, Maurepas and Borgne).

"*f.* The COE will work toward placement of an EWOCDS station above La Place.

"*g.* In addition to wetlands, we should pursue using non-wetland systems for pre-processing diverted water, i.e., headwater stilling basin."

Item 3 addressed operations concerns and is not reproduced here.

"Item 4 -- Other Findings and Recommendations Beyond Original Charge

"1. Investigate the possibility of smaller local diversions to provide sediments to the La Branche and Lake Maurepas wetlands.

"2. Repair leakage in the existing Bonnet Carré structure to provide better control of the flow entering the wetlands and to prevent hazardous spills from entering the wetlands and the Lake during high water periods.

"3. The Steering Panel request Congress to pass the additional authorization necessary to construct a sill or other barrier across the IHNC, as soon as possible.

"4. State of Louisiana & COE assess potential financial exposure from oyster and other fisheries dislocations due to the project, and ways of fixing or avoiding that exposure.

"5. Immediately notify Mr. Allen Ensminger of the progress made during the retreat, and that overland flow through La Branche wetlands was unanimously endorsed."

Committee on Tidal Hydraulics Review

An analysis by the Committee on Tidal Hydraulics (CTH), Corps of Engineers, U. S. Army (CTH 1996) concluded that :

1. Saltwater flux from the Mississippi River-Gulf Outlet (MRGO) to Lake Borgne and the Gulf Intracoastal Waterway (GIWW) through direct connections may provide a significant contribution to the salinity of the lakes and Biloxi Marshes.

2. A numerical model should be used to evaluate diversions and other measures. It should include Lake Pontchartrain, Lake Borgne, the MRGO, the Inner Harbor Navigation Channel (IHNC), the GIWW, the Rigolets, the Chef Menteur, a segment of Mississippi Sound, of Chandeleur Sound, and of Breton Sound as required to provide suitable boundary conditions, and at least a portion of the Biloxi Marshes.

3. The numerical model should be verified to field observations, including salt flux through the MRGO-Lake Borgne connections.

4. The numerical model should be used to conduct experiments for:

   a. The effect of closing the IHNC at Seabrook.

   b. The effect of constructing a jetty and sill at the Lake Pontchartrain end of the IHNC.

   c. The effect of controlling salt flux from MRGO to Lake Borgne.

   d. Evaluating artificial destratification of the MRGO.

   e. The effect of supplemental freshwater diversions into the IHNC-MRGO via the Mississippi River lock.

Objectives

The objectives of the work presented in this report were as follows:

a. Predict the average salinity changes that will be effected in the Lake Pontchartrain Basin, particularly that part known as the Biloxi Marshes in Louisiana and Mississippi, by freshwater diversions through the Bonnet Carré floodway and other measures.

b. Define what freshwater diversion rates will be required to meet specified salinity targets in the Biloxi Marshes, where the salinity targets are based on optimizing oyster production.

The purpose of this report is to present the results of a numerical model investigation addressing these objectives.

2 The Lake Pontchartrain Basin

The Lake Pontchartrain Basin, consisting of Lakes Maurepas, Pontchartrain, and Borgne, the Biloxi Marshes, and Chandeleur Sound plus associated marshlands and waterways, is described in detail by the New Orleans District (USAED, New Orleans, 1984, 1990), Pankow et al. (1989), and CTH (1995). Only the most pertinent factors will be summarized here.

Hydrology

The largest tributary to the area is the Pearl River, with a mean annual flow of about 10,000 cfs, which discharges into Lake Borgne near the mouth of The Rigolets, one of three tidal waterways out of Lake Pontchartrain. Several smaller rivers flow into Lakes Pontchartrain and Maurepas, the largest of which are the Amite, Tickfaw, Tangipahoa, and Tchefuncta Rivers. Average annual freshwater flow into Lake Pontchartrain is about 3,800 cfs.

Freshwater discharge data

The U.S. Geological Survey (USGS) reports daily gaged river discharge from selected stations in the Water Resources Data publication series (e.g., USGS 1982). The daily values are combined into monthly and annual totals, which are used to compute mean discharges, an arithmetic mean of the daily discharges. Multiplying a monthly mean daily discharge by the number of days in the month yields the total flow for the month in cfs-days. Recent discharge reports also include the statistical measure of 50 percent exceedance, which is the daily discharge equaled or exceeded on 50 percent of the days of record. In the mean discharge calculation, a single day of extremely high flows can significantly alter the monthly mean discharge because its contribution is weighted by the flow rate; however, it contributes only one day of high flow to the 50 percent exceedance computed value. Therefore, mean discharge values are higher than 50 percent exceedance discharge values.

This analysis used both mean discharges and 50 percent exceedance discharges, according to the intended use. Reproducing a particular year used mean discharges so that the period's total available fresh water was supplied to the model. Predicting a typical year used the 50 percent exceedance discharges in order to represent a statistical norm and be consistent with the design documents.

Ungaged watershed estimates

The discharge data described in the preceding section were obtained for the most downstream station on each river, then adjusted to compensate for rainfall runoff from the basin below the gage location. The adjustment employed the equation:

$$Q_{adjusted} = F\ (Q_{gaged}) \tag{1}$$

where Q is discharge in cfs and F is a factor computed by one of several methods, the simplest of which is the ratio of total basin surface area to basin area above the gage location. Annual values for the factor F are shown in Table 3. Van Beek et al. (1982) and Pankow et al. (1989) employed monthly adjustment factors which yield the annual values of Table 3.

Table 3
Ungaged Watershed Factors (F) for Annual Discharges

Source	Lake Pontchartrain	Pearl River
Sikora and Kjerfve (1985)	1.06 to 2.4	1.08
van Beek et al. (1982)	3.35	1.18
Pankow et al. (1989)	1.70	1.37
Calculated from drainage areas	Not Calculated	1.32

Tributary discharges used in these analyses were derived from USGS records (e.g., USGS 1982) and Pankow et al. (1989). The monthly tributary flows given in Table 2 and plotted in Figure 2 are 50 percent exceedance values.

Hydrodynamics

Tides in the basin are principally diurnal, with mean ranges of 0.3 ft (Lake Maurepas) to 0.5 ft (Lake Pontchartrain) to 1.4 ft (Chandeleur Sound).

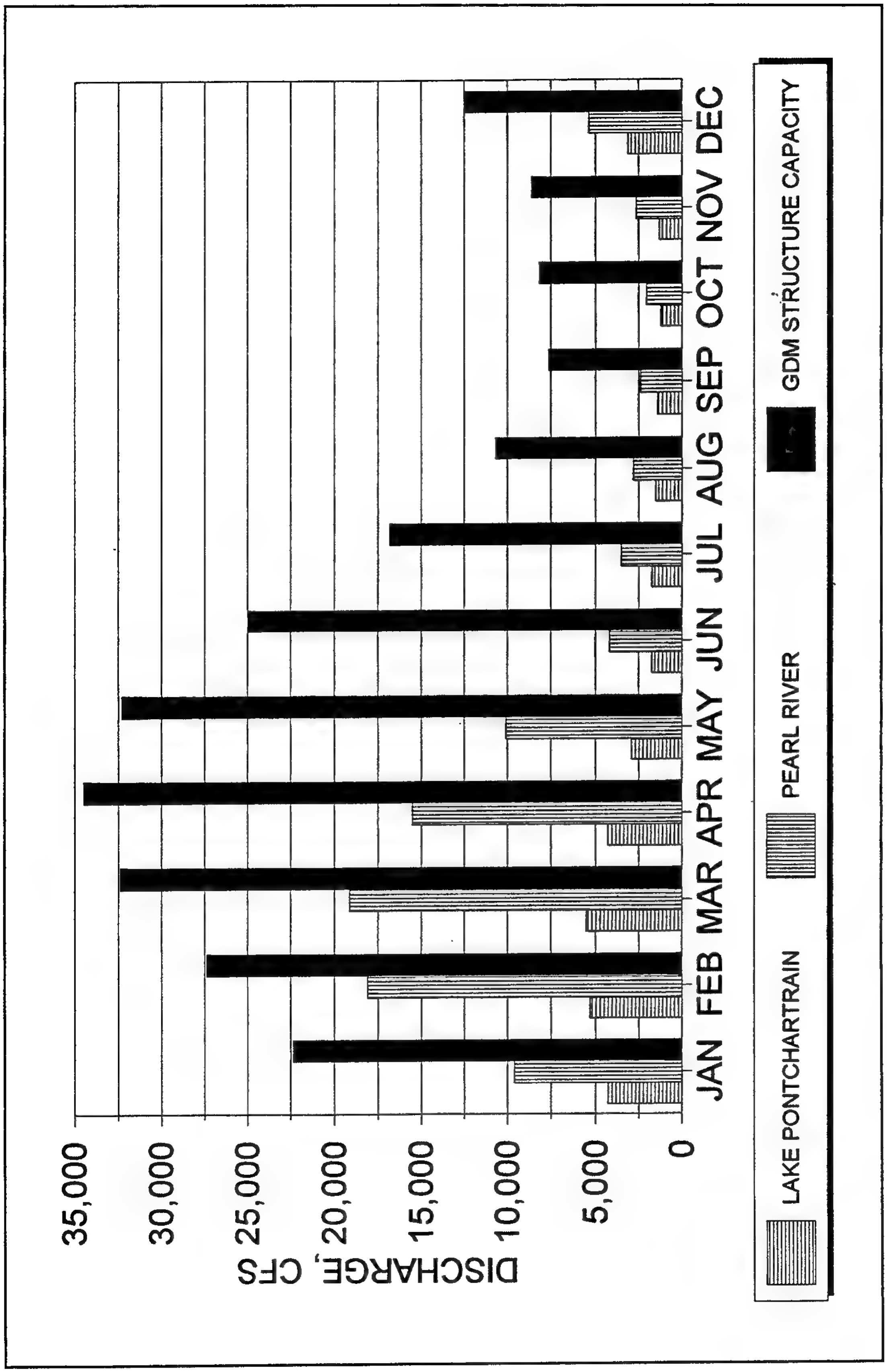

Figure 2. Tributary 50 percent exceedance flows and Bonnet Carré structure design capacity

Sustained winds can raise or lower peak astronomical tide levels by several feet for short periods. Mean water levels are affected by winds, freshwater runoff, and seasonal trends in the Gulf of Mexico.

Figure 3 illustrates typical seasonal variability in mean water level (mwl). It displays monthly mean water levels for 1940-1950 at Eugene Island at the Gulf entrance to Atchafalaya Bay, (USAED, New Orleans, 1982), which are representative of Gulf levels throughout the area in that mean water levels are lower in winter and midsummer and higher in spring and fall.

Currents and circulation are controlled by tides, winds, freshwater discharges, and Gulf currents. Flows in the MRGO are also affected to some extent by density currents (Donnell and Letter 1991).

Salinities

Salinity in the system ranges from completely fresh to 34 ppt depending on location and freshwater flow. The CTH (1995) concluded that Lake Pontchartrain salinities were higher after 1963 construction of the MRGO by 2.1 ppt at Chef Menteur, 1.1 ppt at the North Shore, and 0.3 ppt at Pass Manchac.

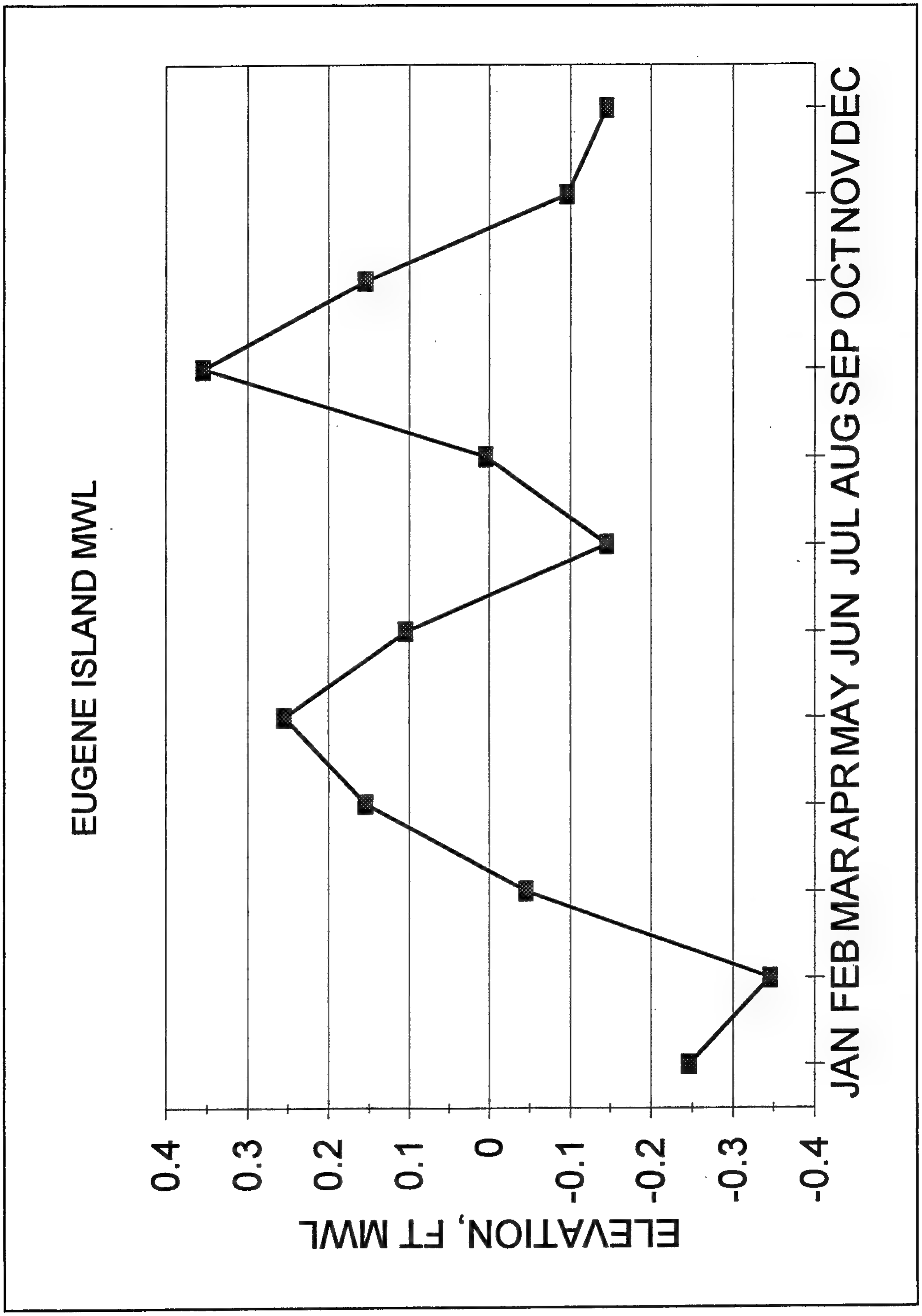

Figure 3. Intra-annual mean water level variation at Eugene Island, 1940-1950

3 Approach

Numerical Model

The numerical modeling code used in this application was RMA10-WES, which was originally developed by Dr. Ian King of Resource Management Associates and modified at the U.S. Army Engineer Waterways Experiment Station. It represents three-dimensional hydrodynamics and salt transport using a finite element solution to the equations of mass and momentum conservation. It accounts for unsteady river inflows, tides, wind effects, and density-driven circulation. The model is described more fully in Appendix A. It has been used to model three-dimensional hydrodynamics and salinity at numerous locations throughout the country, including Galveston Bay, Texas (Berger et al. 1995).

Computational Mesh

Figures 4 and 5 illustrate the planform view of the computational mesh used. Figure 4 is the overall mesh, and Figure 5 is an enlarged view of the area between Lakes Pontchartrain and Borgne to highlight the passes and interconnecting channels. The mesh was three-dimensional everywhere except near the gulfward boundary and in Lake Maurepas.

Experimental Conditions

Two historical periods — March to July 1982 and March to May 1994 — were modeled in the verification process, and those experiments are reported later in this report. For the base and plan experiments, model typical conditions were based on statistical measures. Specifics of the experimental conditions are addressed in the following sections.

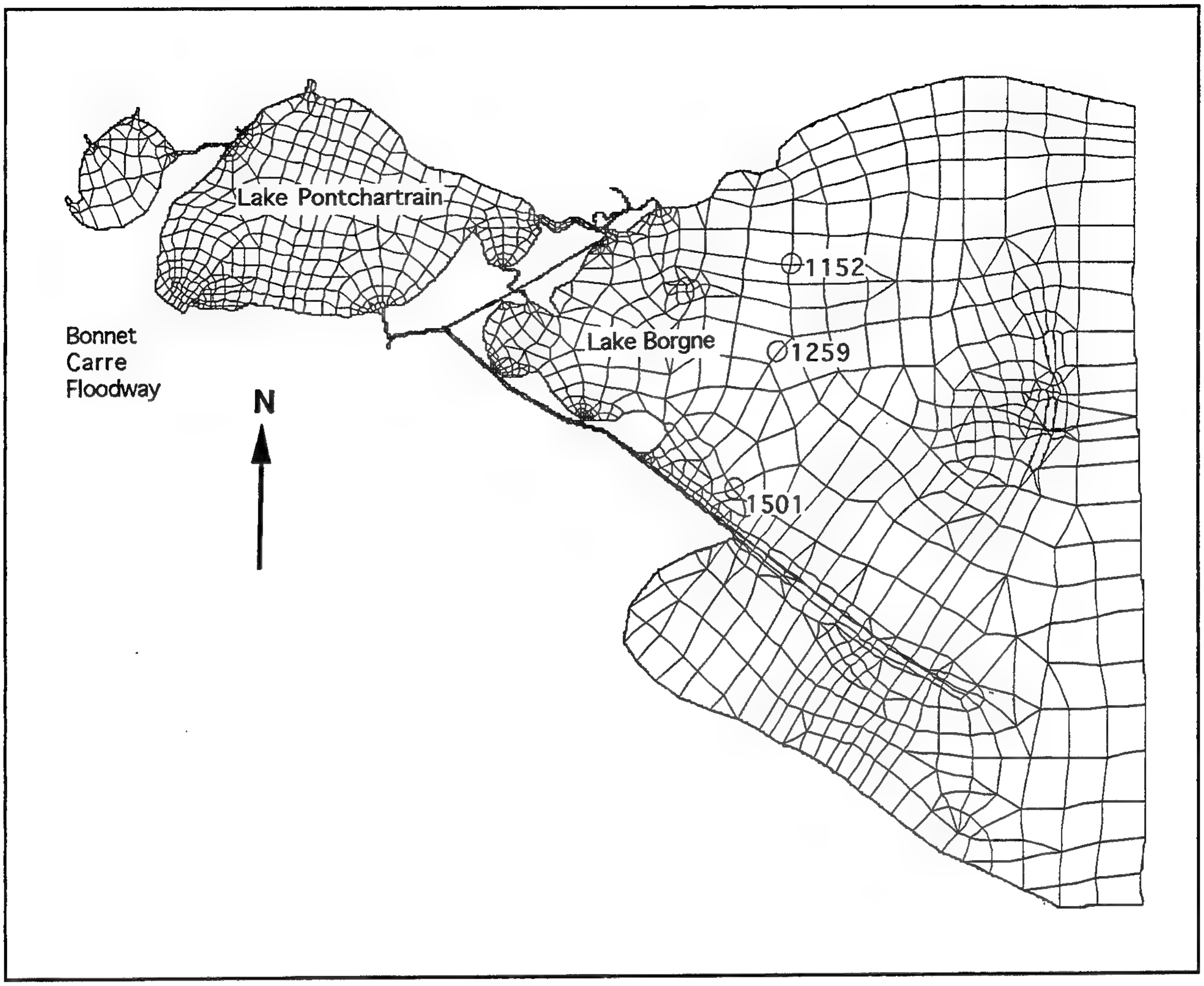

Figure 4. Numerical model mesh and nodes used in analysis

Boundary conditions

Riverflows for the verification periods. For the 1982 verification period, the flow into the Lake Pontchartrain was based on measured mean monthly tributary flows (USGS 1982), adjusted for ungaged area by Equation 1 and using the coefficients developed by Pankow et al. (1989) as given in Table 3. Table 4 shows the flows used for the 1982 verification period and Table 5 shows them for the 1994 period.

During the 1994 verification period, an experimental release of water through the Bonnet Carré structure permitted several thousand cubic feet per second to flow into Lake Pontchartrain. The estimated flow release through the floodway during the period is shown in Figure 6 .

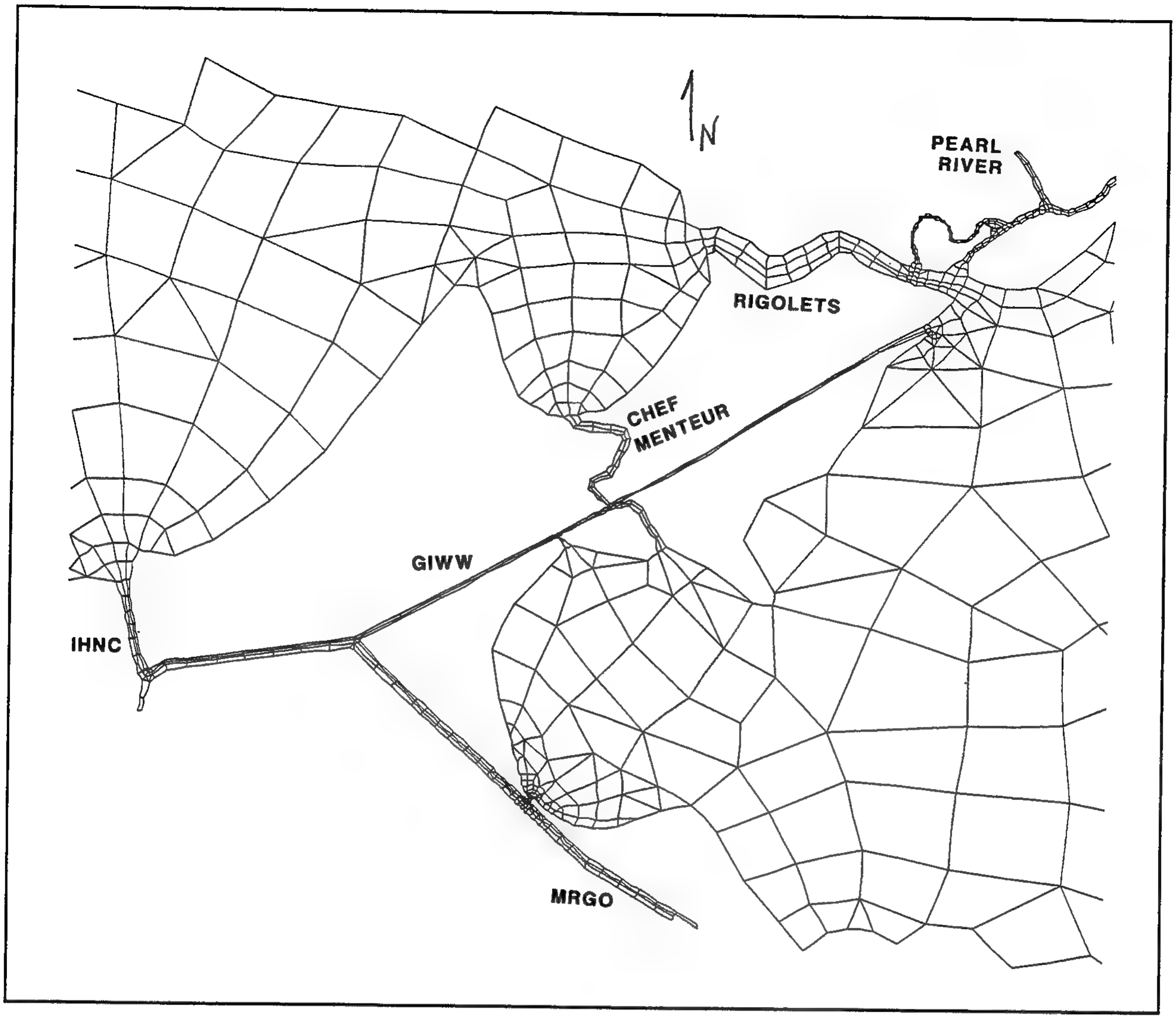

Figure 5. Details of model mesh

Table 4 Stream Inflow for 1982 Verification Period, cfs						
Month	**Pearl**	**Amite**	**Blind**	**Tangipahoa**	**Tickfaw**	**Tchefuncta**
March	16,330	2,344	510	99	482	132
April	15,723	5,513	510	246	850	328
May	9,909	1,905	510	108	372	145
June	3,473	961	510	62	202	83
July	3,931	1,129	510	73	226	97

Table 5
Stream Inflow for 1994 Verification Period, cfs

Month	Pearl	Amite	Blind	Tangipahoa	Tickfaw	Tchefuncta
March	26,194	7,155	728	238	1,212	243
April	21,235	5,569	566	187	942	189
May	13,823	3,805	386	128	644	129

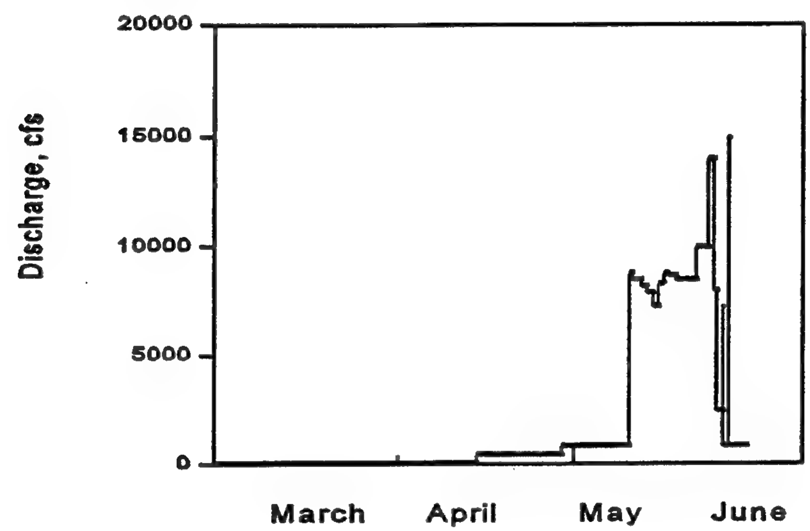

Figure 6. Modeled release through the Bonnet Carré Floodway during 1994 experimental diversion

Riverflows for base and plan experiments. Base and plan experiments were conducted for typical conditions, using the 50 percent exceedance flows described earlier and given in Table 2. The total flows into Lake Pontchartrain were subdivided into the various streams proportionally by multiplying the monthly 50 percent total flow by the ratio of the monthly average flow from each of these streams to the total average flow. (This calculation assumes that the 50 percent flows exhibit the same statistics as the mean flows, which is not precisely true, but is sufficient for this purpose.) Table 6 lists the particular streams and gages used for this exercise. The average monthly flow in each of these streams is shown in Table 7 and the resulting distribution of 50 percent exceedance flows is given in Table 8.

Table 6
Streams and Gauges Used to Distribute Lake Pontchartrain Total Tributary Flows

Stream (Location)	No. of Years	Coverage Years	USGS Station ID
Amite (Denham Springs, LA)	57	1914, 1938-1993	07378500
Tangipahoa (Robert, LA)	55	1939-1993	07375500
Tickfaw (Holden, LA)	53	1941-1993	07376000
Tchefuncta (Folsom, LA)	50	1944-1993	07375000
Natalbany (Baptist, LA)	51	1943-1993	07376500

Table 7
Lake Pontchartrain Tributaries Average Monthly Streamflow, cfs

Month	Amite	Tangipahoa	Tickfaw	Tchefuncta	Natalbany	Total
January	3,283	1,608	588	242	180	5,901
February	3,937	2,036	731	305	255	7,264
March	3,618	1,839	654	257	208	6,576
April	3,409	1,801	618	251	200	6,279
May	2,212	1,198	399	165	117	4,091
June	1,271	798	230	95	57	2,451
July	1,167	775	199	92	53	2,286
August	1,113	732	214	98	62	2,219
September	1,032	729	214	92	62	2,129
October	893	560	152	66	33	1,704
November	1,180	766	230	126	80	2,382
December	2,390	1,327	442	199	145	4,503

The flow from the Natalbany enters the Tickfaw so its discharge was added to the Tickfaw. Blind River was included in the previous work with an estimated average inflow of 300 cfs. For consistency it was included, and the other streams entering Lake Maurepas were reduced accordingly. The total of 216 cfs was then put into the Blind River. It is doubtful that this distribution makes any difference to Lake Pontchartrain, but it is a consistent way to derive the flows and reflects the thoughts from the two-dimensional study.

Table 9 contains the final flows used for the base and plan experimental program (not including the Bonnet Carré releases). Base and plan experiment river inflows were those shown in Table 9, with the various specified diversions of flow through the Bonnet Carré Floodway. The Base or No

Table 8
Distribution of the 50 Percent Exceedance Flows, cfs, in the Lake Pontchartrain Tributaries

Month	Amite	Tangipahoa	Tickfaw	Tchefuncta	Natalbany
January	2,368	1,160	424	175	130
February	2,862	1,480	531	222	185
March	3,016	1,533	545	214	173
April	2,316	1,223	420	170	136
May	1,576	853	284	118	83
June	886	556	160	66	40
July	876	581	149	69	40
August	753	495	145	66	42
September	672	475	139	60	40
October	622	390	106	46	23
November	637	413	124	68	43
December	1,643	912	304	137	100

Table 9
Final Stream Inflow for Testing Program, cfs

Month	Pearl	Amite	Blind	Tangipahoa	Tickfaw	Tchefuncta
January	9,602	2,194	216	1,160	512	175
February	18,060	2,689	216	1,480	674	222
March	19,120	2,842	216	1,533	676	214
April	15,510	2,142	216	1,223	514	170
May	10,090	1,402	216	853	325	118
June	4,178	713	216	556	158	66
July	3,522	702	216	581	147	69
August	2,792	579	216	495	145	66
September	2,388	499	216	475	137	60
October	2,047	448	216	390	87	46
November	2,651	463	216	413	125	68
December	5,339	1,468	216	912	362	137

Diversion Plan is obvious in that no flow passed through the floodway. The plan flows are discussed later.

Tides. Tides at the model's gulfward boundary were synthesized for the years 1982 and 1994 from the tidal constituents as given by Outlaw (1982) and shown in Table 10. The mean water level was set to zero referred to the National Geodetic Vertical Datum (NGVD).

Wind. The wind data used were obtained from the U.S. Air Force Environmental Technical Applications Center in Asheville, NC. These data were the hourly surface winds at the New Orleans International Airport for the calendar year 1982 and for May 1994. The 1982 data were used for all base and plan experiments.

Table 10
Gulf Boundary Tidal Constituents

Tidal Constituents		South End of the Boundary		South of Ship Island		North End of the Boundary	
Component	Period hr	Amplitude ft	Epoch deg	Amplitude ft	Epoch deg	Amplitude ft	Epoch deg
O1	25.819	0.46	-37.4	0.51	-37.4	0.36	-50.4
K1	23.934	0.47	-38.6	0.51	-38.8	0.36	-50.2
P1	24.066	0.15	305.6	0.15	310.3	0.14	289.1
M1	24.833	0.01	323.7	0.02	328.2	0.00	329.1
J1	23.099	0.02	282.7	0.02	267.1	0.02	289.1
Q1	26.868	0.11	-40.8	0.12	-39.5	0.07	-57.5
M2	12.421	0.09	239.5	0.09	252.9	0.04	214.4
S2	12.000	0.05	264.1	0.05	284.8	0.03	235.0
N2	12.658	0.02	209.4	0.02	223.0	0.01	183.8

Initial conditions

The initial solution for the model hydrodynamics (currents and water level elevations) was zero velocity and mean water level throughout the system. Since these parameters propagate at roughly the long-wave celerity, they quickly reached a stable solution independent of initial conditions. Salinity, however, is propagated at the speed of a water particle and so (for subcritical flow) an initial solution estimate error can take a very long time to be effectively eliminated. In these experiments an initial salinity field was generated from previous two-dimensional results and then the model was run for 90 days with repetitive March 1982 tides and tributary flows to generate a reasonable and stable salinity field throughout the system. That hydrodynamic

and salinity solution was saved to a file and used as initial conditions for all subsequent experiments for verification and base and plans.

Sensitivity experiments showed that tributary flow changes had a noticeable residual effect in Biloxi Marsh salinities for about 4 months; therefore, to generate salinity estimates beginning in April for the base and plans, the model was run with January through March tides and tributary flows (including Bonnet Carré diversions for the plans) before running the desired period of April through August. For Plan RT only, the experiment ran through October.

Base and plans

Three flow conditions were modeled to define the effects of freshwater diversion for the existing geometry of the system (no new structures other than the Bonnet Carré Diversion structure.) In addition, one experiment with a structural alteration was conducted. All employed the boundary and initial conditions described previously. Table 11 lists the diversion schedule for Plan RT and Plan MBP5. Experiments were as follows:

a. Base: No diversion, zero flow through Bonnet Carré.

b. Plan RT: Reduced target diversions, diversion flows ranging up to 20,000 cfs.

c. Plan MBP5: Diversion flows ranging up to 8,500 cfs.

d. Plan LBC1: No diversion, connections between MRGO and Lake Borgne closed.

The existing conditions model mesh (Figures 4 and 5) provided three connections between MRGO and Lake Borgne: direct connections at Shell Beach and Martello Castle and one connecting Lake Borgne to the GIWW near Bayou Gentilly (southeast of Chef Menteur). These connections were sized to approximate not only the connections at those locations, but also nearby smaller connections; thus, they represent an aggregation of several smaller waterways. In Plan LBC1 all three of these connections were totally closed. The Chef Menteur connection to Lake Borgne was left open.

The numerical model calculated water-surface elevations, current velocities (three-dimensional components), and salinities at each node every 60 minutes for the 8-month period of simulation. Those data were processed to provide average monthly salinity contour plots for base and each plan and monthly average salinities at a number of points in the Biloxi Marshes as shown in Figure 4.

Table 11
Plan Diversion Schedules, cfs

Month	Plan RT	Plan MBP5
January	1,000	4,000
February	6,000	8,500
March	20,000	8,500
April	20,000	8,500
May	0	0
June	5,000	6,000
July	6,000	8,500
August	3,000	5,300
September	7,000	3,800
October	8,150	0
November	5,000	0
December	0	0

Regression Analysis

The numerical model's point values of salinity were used in a regression analysis to develop an easily and rapidly applied method for computing approximate monthly average salinities throughout the year and for diversions different from those cited in the previous section without resorting to full numerical experiments.

The regression was built on previous work by Pankow et al. (1989) and USAED, New Orleans (1984), in which dozens of regression relationships were tried using field observations of salinity as the dependent variable and numerous forcing functions (e.g., freshwater inflow, tides, winds, rainfall, etc.) as independent variables. Those analyses confirmed the common-sense conclusion that river inflow dominates monthly average salinities in the Biloxi Marshes, but showed that shorter term salinity variations were affected appreciably by wind, precipitation, and mean water level.

Pankow et al. (1989) found that the equation form best relating discharges to salinity was:

$$S = A \, Ln \, (P') + B \, Ln \, (LP') + C \qquad (2)$$

where,

S = average monthly salinity

A, B, and C = constants

Ln = natural logarithm

P' = lagged, weighted, and normalized Pearl River monthly discharges

LP' = lagged, weighted, and normalized Lake Pontchartrain tributaries monthly discharges

Pankow used lagged correlation analysis to weight the effects of the preceding month's discharges on this month's salinity and found that the effects were best described by:

$$P' = (0.22\ P_0 + 0.37\ P_i + 0.25\ P_2 + 0.11\ P_3 + 0.05\ P_4)/10{,}000 \qquad (3)$$

$$LP' = (0.17\ LP_0 + 0.40\ LP_i + 0.25\ LP_2 + 0.12\ LP_3 + 0.06\ LP_4)/3{,}800 \qquad (4)$$

where

P = total month discharge, cfs-days, of the Pearl River

LP = total month discharge of the Lake Pontchartrain tributaries plus the Bonnet Carré Diversion

0,1,2,3,4 = subscripts indicating present month and first, seconds, third, and fourth preceding months, respectively

The monthly weights in Equations 3 and 4 were calculated by Pankow et al. (1989) from field observations to quantify each month's relative contribution to a given month's salinity based on the lag time between flow and salinity effect. Equation 10a from their report employed the first two terms of Equation 3 and the middle three (months 1, 2, and 3) terms of Equation 4. The Pankow weights for the additional months were used in this analysis because the new model results suggested noticeable salinity effects for up to 4 months after an increase in discharge, and because the model's lack of noise (e.g., variation in salinities due to short-term fluctuations in flows and other forcings) permitted the lower magnitude effect of past months to be reasonably included.

The weighting coefficients in Equations 3 and 4 are derived from field data and not from the regression against model data described in the next chapter. However, a visual inspection of salinities from the 1983 floodwater diversion (up to about 274,000 cfs daily average flow) showed that Biloxi Marsh salinities rebounded to prediversion levels in about 1 month.[1] While that does not invalidate the weights of Equation 4, it does indicate that individual events may deviate substantially from the form of that equation. Equation 4 is examined further in Chapter 5.

[1] Personal communication with Burnell Thibodeaux of the New Orleans District, June 1996.

4 Numerical Model Verification

The model verification consisted of comparison with field data from the literature. The primary comparisons were made to tide elevations and to salinity. The period of March through July 1982 was selected as the primary comparison period since there were salinity field data from both Lake Pontchartrain and the Biloxi Marshes area during the period. The Biloxi Marshes data consisted of surface samples at several sites in the marsh area taken at distributed times by the Louisiana Department of Wildlife and Fisheries. Lake Pontchartrain data came from Shurtz and St. Pé (1984). This same period was used to analyze the tidal elevation results from the model with the harmonic constituents calculated by Outlaw (1982).

A secondary comparison was made with data collected near the Bonnet Carré Floodway during the 1994 experimental diversion.

Tides

Model and field tides were compared at stations shown in Figure 7. Data from the numerical model on 1-hour increments over 5 months of the verification period were used for the analysis. Since these data were generated from a boundary tide consisting of astronomical data only, no filtering was necessary. The results of the harmonic analysis, shown in Table 12, consist of the three major diurnal components for seven stations. The amplitude of each component for the model and prototype is the first entry at each station. The second entry (on all but station B2) is the phase lag in hours from Station B2. The composite results are easier to follow, which are the root sum of the squares of each of these components, given by

$$a_c = [(a_{kl})^2 + (a_{01})^2 + (a_{pl})^2]^{1/2} \qquad (5)$$

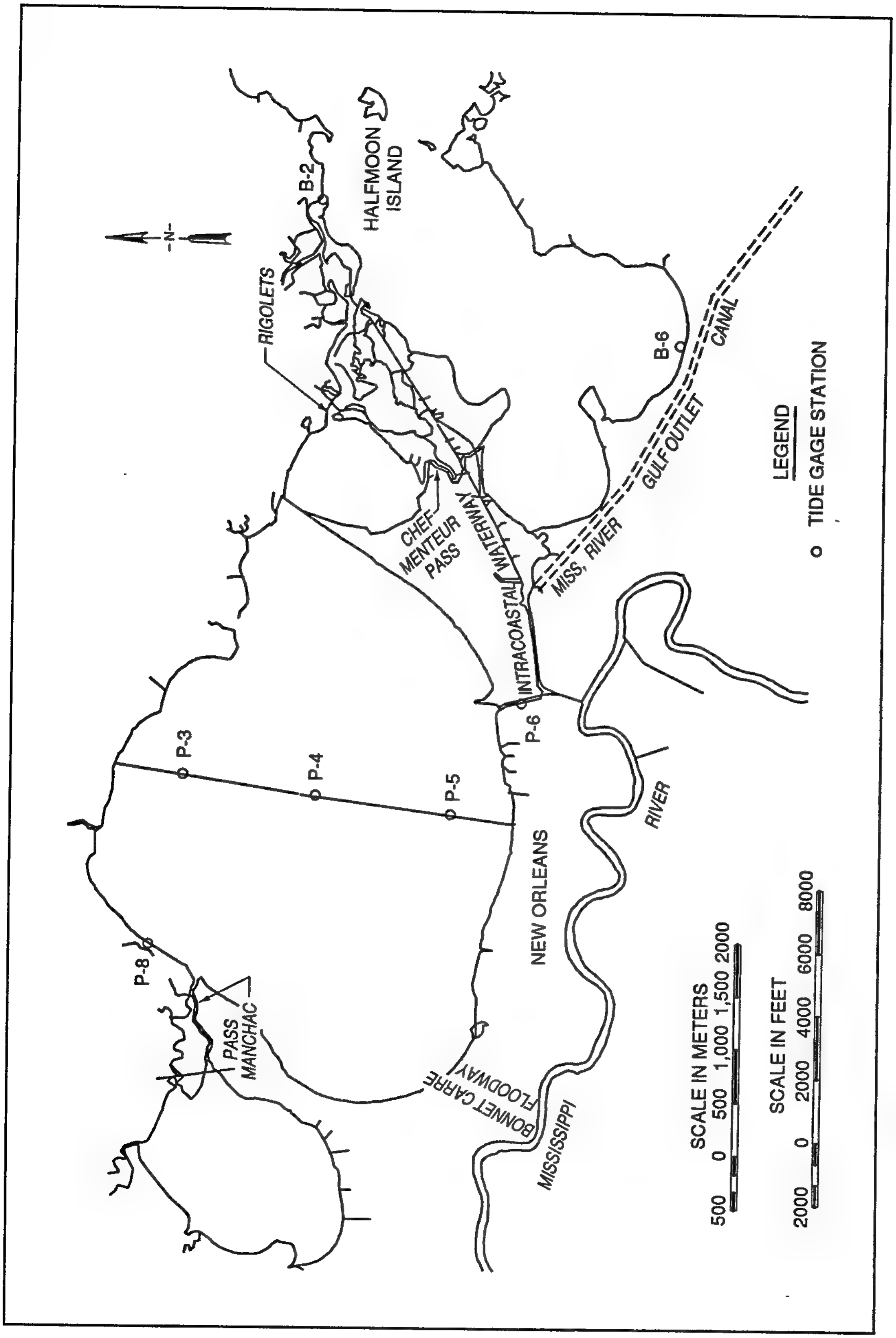

Figure 7. Field tide gauge stations

Table 12
Water-Surface Elevation Harmonic Analysis, Amplitude and Phase

Station	B2	B6		P3		P4		P5		P6		P8	
	A	A	P	A	P	A	P	A	P	A	P	A	P
Component:: K1 - 23.93 hr													
Prototype	0.39	0.41	1.1	0.13	6.8	0.10	7.4	0.11	7.1	0.21	2.9	0.10	7.7
Model	0.37	0.36	0.8	0.09	6.4	0.09	6.4	0.09	6.4	0.10	3.0	0.09	6.5
Component:: O1 - 25.82 hr													
Prototype	0.35	0.32	1.0	0.10	6.5	0.10	7.5	0.10	7.8	0.17	3.1	0.08	7.5
Model	0.36	0.34	0.8	0.09	6.8	0.09	6.8	0.09	6.8	0.10	5.4	0.09	6.9
Component:: P1 - 24.07 hr													
Prototype	0.17	0.14	2.0	0.05	5.1	0.03	7.9	0.03	6.4	0.07	3.1	0.03	7.8
Model	0.10	0.10	0.8	0.03	6.2	0.02	6.2	0.02	6.2	0.03	3.0	0.03	6.3
Composite													
Prototype	0.55	0.54	1.40	0.17	6.1	0.14	7.6	0.15	7.1	0.28	3.0	0.13	7.7
Model	0.53	0.51	0.8	0.13	6.5	0.13	6.5	0.13	6.5	0.14	3.8	0.13	6.6

NOTE: A = Amplitude, ft
P = Phase lag, hours

where

a_c = composite amplitude

a_{k1} = K1 component amplitude

a_{o1} = O1 component amplitude

a_{p1} = P1 component amplitude.

The composite phase lag is a simple arithmetic average

Stations B2 and B6 are near the Gulf and Lake Borgne, while stations P3, P4, P5, and P8 are within Lake Pontchartrain. Station P6 is in the IHNC.

The composite diurnal amplitude in Lake Borgne was between 0.5 and 0.6 ft, while in Lake Pontchartrain the amplitude was damped to less than 0.2 ft. The phase lag between Lake Borgne (given by Station B2) and the center of Lake Pontchartrain was about 7 hours. The comparison of model with prototype shows that within Lake Pontchartrain the amplitude was only 0.02 to 0.03 ft low. The model showed a lag at Station B6 of 0.8 hour versus 1.4 hours in the field data, so the model was roughly 1/2 hour ahead. Within Lake Pontchartrain the model showed an amplitude between 0.00 and 0.04 ft

low compared to the field analysis. The model phase lag was generally less than that of the field. For these lake stations the model showed a phase lag of 6.5 or 6.6 hours, while the field data showed a lag of 6.1 to 7.7 hours. Generally, the model preceded the field by approximately 1 hour. Station P6 in the IHNC showed a composite amplitude of 0.14 ft in the model and 0.28 ft in the field data, the weakest comparison in the model and due perhaps to inadequate mesh resolution of the IHNC. The model phase lag was 3.0 hours versus 3.8 hours prototype. A phase lag of only 3.8 hours demonstrates that the tidal influence is derived primarily from Lake Borgne rather than from Lake Pontchartrain, an expected result since the MRGO is considerably deeper than Lake Pontchartrain and the tide propagates more quickly through the canal.

Tidal Prism

The tidal prism volume contributions from the major tidal passes of Lake Pontchartrain were estimated by Swenson and Chuang (1983) to be 3.4×10^9, 1.8×10^9 and 0.25×10^9 ft^3 for Rigolets, Chef Menteur, and IHNC, respectively. The CTH estimates for the same three connections were 3.1×10^9, 1.6×10^9, and 4.2×10^9 ft^3, respectively (CTH 1995). The model results showed values of 3.2×10^9, 0.95×10^9, and 1.3×10^9 ft^3, respectively, for these three passes. The model matched the estimates for tidal volume in Rigolets Pass fairly well; however, IHNC appears to be about 5 times the estimate of Swenson and Chuang but considerably smaller than the CTH estimate. At the cross section used in the model study, the cross-sectional area was approximately 30,000 ft^2, which results in an average cross-section flood velocity of about 0.2 fps. The model predicted an average cross-section flood velocity of 1 fps. In a nearby location, Outlaw (1982) shows velocities of up to 2.5 fps. Further validation of the model tidal prism is supplied in the following section in which model velocities are compared with field measurements; therefore, while the model results do not agree fully with either prior estimate, the model results are reasonable.

Velocities

While there are no directly comparable velocity data for the periods of salinity verification, the synthesis of the current data analyzed by Outlaw (1982) can provide useful information to demonstrate model performance. Table 13 shows the results of Outlaw's data (prototype October 1978) compared with the average cross-section velocity calculated in the model.

The model velocities are the cross-section average velocity for ebb and flood over the month. The prototype values are the geometric mean of all the harmonic constituents plus residual from Outlaw (1982). In all cases "flood" is considered the inland direction. For some areas, such as the two openings

Table 13
Model and Prototype Velocity Comparison, fps

Station	Direction	Prototype Oct. 1978	Model Apr. 1982	Model July 1982
Shell Beach	Flood	1.0	1.2	1.3
	Ebb	0.7	1.0	1.2
Martello Castle	Flood	0.5	0.9	1.0
	Ebb	0.5	1.0	1.1
GIWW	Flood	0.1	0.2	0.3
	Ebb	0.4	0.3	0.3
IHNC	Flood	0.9	1.0	0.9
	Ebb	0.9	0.9	0.9
Chef Menteur	Flood	0.8	0.7	0.7
	Ebb	0.7	0.9	0.9
Rigolets	Flood	0.5	0.8	0.9
	Ebb	0.7	1.2	1.2

from MRGO to Lake Borgne and the GIWW, that are somewhat difficult to discern, the closer direction toward Lake Borgne was chosen as "ebb." The comparisons show that the model results are reasonable. The model shows generally higher current magnitudes in the Rigolets and Martello Castle Passes. The other areas compare quite well.

Salinity

The primary model verification for salinity includes a comparison with field data collected in the principal area of interest—the Biloxi Marshes region. Salinity field data consisted of analyzed grab samples by the Louisiana Department of Fisheries and Wildlife, which were supplied by the New Orleans District. Field and model data comparisons are shown in Plates 1-3. (Station locations are shown in Figures 7 and 8.) Table 14 contains relevant statistics describing the comparison of model and field data based on a very limited number of field observations.

The statistic d (Willmott 1982; Willmott et al. 1985) is defined as:

$$d = 1 - \frac{\sum (M_i - P_i)^2}{\sum (|M'_i| + |P'_i|)^2} \tag{6}$$

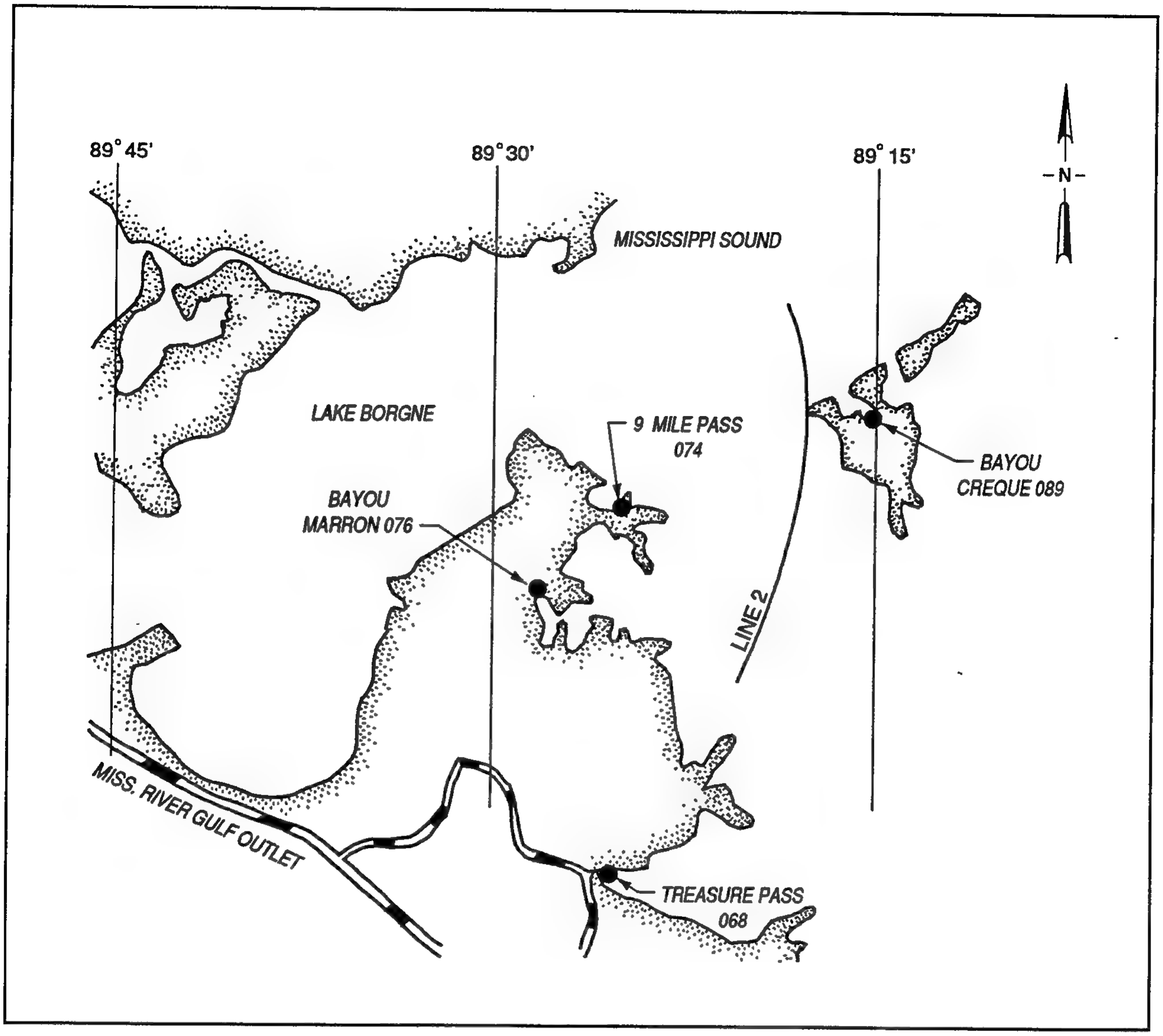

Figure 8. Wildlife and Fisheries field salinity stations

Table 14
Salinity Comparison Statistics

Station	Statistic *d*	Hourly		Monthly Difference (model-prototype) ppt
		Mean Absolute Error |(model-prototype)| ppt	Mean Difference (model-prototype) ppt	
068	0.47	2.2	-1.7	-0.2
074	0.61	2.4	1.7	-0.6
076	0.32	0.9	0.2	-1.4

where

M_i = model reading i

P_i = prototype reading i

M'_i = model reading i minus the average of all prototype values

P'_i = prototype reading i minus the average of all prototype values

This statistic d ($0 \leq d \leq 1$) is generally a good indication of the model's ability to follow trends and also is good at picking up shifts in salinity. In this case, all of these stations make weak daily comparisons due to there being very little trend in the field data, which indicates that the fluctuations shown in the field data are reflected in other physical forcings besides river inflow and astronomical tides, such as short-duration storms and meteorological circulation. However, the model is being used to predict monthly average salinity and so these discrepancies do not significantly limit the model's usefulness. (The model employed representative winds, so the longer term effects of wind—increased dispersion and seasonal patterns—were already included.) The d statistic can also be used to compare the overall performance of the model by using data from all three stations. Here the statistic has a value of 0.86, indicating that the spatial distribution of salinity is fairly good. The overall Pearson correlation is about 0.87 between the model and field, also indicating much the same thing as d.

The mean difference for these stations was less than 2 ppt, indicating the shift in salinity at the stations. The Mean Absolute Error (MAE) does not allow positive and negative errors to cancel and so is an indicator of the magnitude of the difference. In this case it is less than 2.5 ppt. The comparison at station 076 is quite good with an average difference of 0.2 ppt. Station 068 shows a mean difference of -1.7 ppt; however, most of the difference is attributable to the last field data entry, which is about 6 ppt higher than the model. The model does not highly resolve the marsh area; however, from Figure 8 one can see that station 068 is near Pass La Loutre, which connects directly to MRGO. After a large freshwater event the salt water will migrate back quickly in MRGO and through Pass La Loutre to this station. The model does not include this channel directly and so responds more slowly.

The monthly average salinity statistics of Table 14 are based on only two or three field observations, far too few to constitute a statistically valid sample. They are included only to help provide some insight into the model accuracy expected.

From these results, it is estimated that the numerical model is capable of predicting instantaneous Biloxi Marshes salinities with an error of about $\pm$ 2 ppt under the range of tides, freshwater flows, and winds occurring during the spring and summer of 1982. While the field observations are too few for a

rigorous statistical analysis, the model error in predicting mean monthly salinities for such conditions is estimated to be about ± 1 ppt.

Lake Pontchartrain isohaline data were available for July 28-29, 1982, and May 1994. Plate 4 shows the field measured salinity in Lake Pontchartrain (Schurtz and St. Pé 1984) and model results, respectively, for July 28-29, 1982, a time in which salt water was intruding into the lake. Overall the model is about 0.5 ppt low as it shows an average lake salinity of about 4.5 and the field data indicate about 5 ppt. The model shows a high intrusion of salt through the IHNC with a concentration of up to 10 ppt. The field data show an even higher salinity entering the lake of about 20 ppt. In both model and field the eastern end of the lake around Rigolets and Chef Menteur have salinities over 6 ppt.

Plate 5 illustrates both numerical model results and field observations from the May 1994 experimental release of Mississippi River water through the Bonnet Carré flood control structure. The isohalines are for May 27, 1994. Field data (solid lines) were provided by the USGS Baton Rouge office. The overall agreement between model and field contours is fairly good even though details are different. Differences in detail are to be expected since the model flow release was distributed uniformly across the floodway instead of flowing in multiple small channels as occurred in nature. Replication of details at this scale would be possible if that were important to the model's intended application; however, since the model's purpose was to examine larger scale salinity patterns, no attempt was made to better resolve those details near the floodway. Plate 5 merely indicates that the model is capable of generally reproducing spread of the freshwater plume.

5 Experimental Results

Numerical Model

By their nature, model results are most appropriately used by comparing one model result with another, for in that way the errors inherent to the modeling are minimized or eliminated. However, in this case, where prototype salinities in the area of interest are not well documented, it is necessary to use absolute salinity values from each plan to fully evaluate that plan. These results should be interpreted in light of the conditions tested and of the model error estimated from the verification experiments.

The detailed model output has been provided in digital form to the New Orleans District for incorporation into their geographical information system and application to oyster productivity and fisheries displacement studies. A summary of the results is given here for documentation purposes.

Plates 6 to 10 display salinity contours for the modeled area for the base and three plans month by month, April through August. Contour displacement gulfward is evident for the diversion plans, with Plan RT pushing the 4-ppt contour completely out of Lake Pontchartrain and Biloxi Marshes salinity contours both shifted and, nearer the Gulf boundary, compressed.

Plan LCB1 freshens the southern lobes of Lake Borgne considerably, from a range of 8-10 ppt for the base to 6.5-8 ppt in April and May. In Lake Pontchartrain the 4-ppt contour is moved gulfward from about the western one-third line to about the eastern one-third line in April and restricted to the area around the passes by May. The degree of salinity change in Lake Pontchartrain is somewhat surprising, but can be heuristically explained by noting that the closure-induced freshening of southern Lake Borgne will reduce the flood phase tidal filling salinity through Chef Menteur by about 2 ppt.

The project design was intended to provide target salinities at a specified zone in the Biloxi Marshes, designated as "Line 2" in the General Design Memorandum (GDM) (USAED, New Orleans, 1990). Model node 1259 lies on that line about the middle of the Biloxi Marshes as shown in Figure 4. Computed salinities at node 1259 are given in Table 15.

Table 15 TABS-MD Model Salinities at Node 1259, ppt							
		Plan RT		Plan MBP5		Plan LBC1	
Month	Base	ppt	Change, ppt	ppt	Change, ppt	ppt	Change, ppt
Apr	13.4	10.2	3.2	11.4	2.0	11.4	2.0
May	13.5	9.9	3.6	11.4	2.1	11.4	2.1
Jun	14.4	11.0	3.4	12.4	2.0	12.2	2.2
Jul	15.7	12.2	3.5	13.2	2.5	13.2	2.5
Aug	17.2	13.0	4.2	13.8	3.4	13.9	3.3

Regression

Fitting the equation

Performing a linear regression on the discharge data of Tables 2 and 11 and Base and Plan RT salinity data of Table 15 to fit the form of Equation 2 (10 observations and 7 degrees of freedom) yielded the following expression for salinity at node 1259:

$$S = -0.844 \, Ln \, (P') - 2.68 \, Ln \, (LP') + 26.4 \tag{7}$$

where P′ and LP′ are defined by Equations 3 and 4. Equation 7 has a correlation coefficient (R^2) of 0.99 and a standard error of 0.25 ppt in the salinity estimate. The high correlation (a value of 1 implies perfect correlation) and low standard error in fitting a range of diversion flows from zero to 20,000 cfs gives confidence that the expression is a good one for forecasting the average salinity effects of diversion flows within that range in the TABS-MD model. It also provides an after-the-fact confirmation that the monthly weights of Equations 3 and 4 are appropriate. (Giving all months equal weight lowered the correlation coefficient to 0.96 and doubled the standard error.) It is concluded that Equation 7 is a good approximation (± 0.25 ppt) of the monthly average Biloxi Marshes salinity response at the location of node 1259 as represented by the numerical model for the months of April through August.

Error estimate

To help evaluate the estimate of total error in Equation 7, Figure 9 displays Equation 7 and the Pankow equation for the base condition along with some field observations. First, it can be seen that Equation 7 produces lower

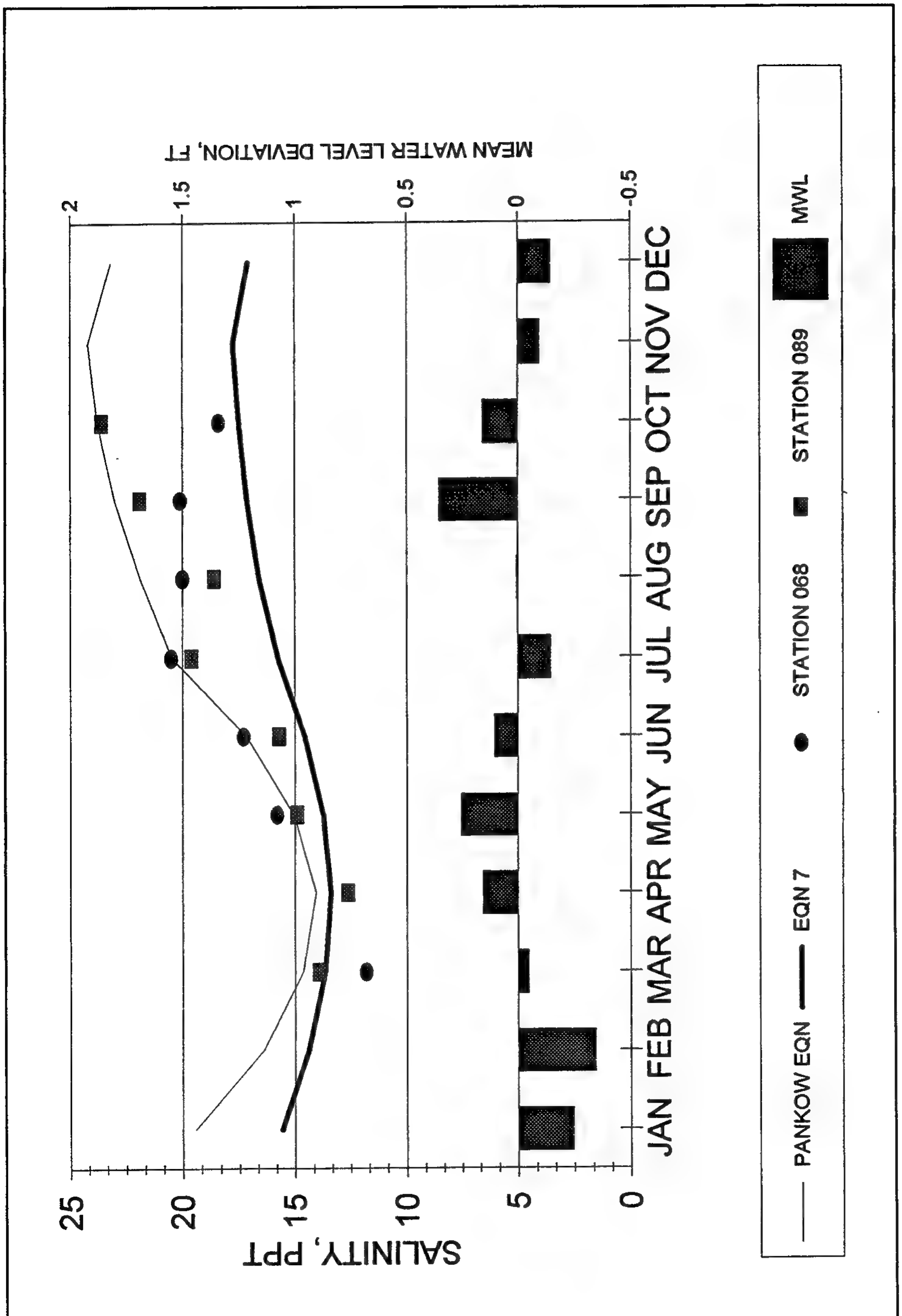

Figure 9. Node 1259 50 percent exceedance salinities

salinities throughout the year than the Pankow equation and displays less intra-annual range. Field observations from the Louisiana Department of Wildlife and Fisheries stations at Bayou Creque (station 089 in Figure 8) and Treasure Pass (station 068 in Figure 8) for the period 1971-1991 were analyzed by the New Orleans District[1] to obtain the 50 percent exceedance salinities plotted as points in Figure 9. Station 089 is east of the north end of Line 2 and Station 068 is west of the south end of the line, so they may be at least a fair approximation of what should be happening at node 1259 near the center of Line 2. They show reasonable agreement (± 2 ppt, about the same as the verification error in spot samples) with both equations during March through June, but fall between the diverging equations in July through October. (Data for December through February were too sparse to get a data point.)

The salinity data of Figure 9 suggest that Equation 7 has too little intra-annual variation in predicted 50 percent salinities. To examine the role that seasonal mean Gulf level might play in that variation, plotted across the bottom of Figure 9 are the variations in mean water from Figure 3. While the correspondence between higher water level in September and observed salinities higher than Equation 7 suggests that adding intra-annual water level variation might improve agreement between the numerical model (and thus Equation 7) and field observations, other months (e.g., July) suggest the opposite. Resolution of the issue awaits further numerical experiments not necessary to attain the objectives of this work.

The above analysis suggests that the Equation 7 error band is approximately equivalent to that of the numerical model for March through June, or about ± 1 ppt in predicting monthly mean salinities for a variety of conditions. For July through February the expected error is larger, but the very limited data do not permit a good estimate of the error. From Figure 9 it is estimated that Equation 7 may yield values 1-3 ppt too fresh for July through October.

Results

Equation 7 is used in the following discussion to predict node 1259 salinities (and by implication, those of Line 2) for the plans subjected to numerical experimentation, extending those results to months beyond those for which numerical model results are available. It is also used to predict salinities for the entire typical year under other diversion scenarios that have not been examined in the numerical model at all. As discussed in the previous section, the use of Equation 7 must be tempered by an appreciation for its expected error. Its use must also be limited in that it applies to only one point, that of node 1259. Thus while the equation may indicate that node 1259 salinity may be slightly fresher or slightly saltier than the Chatry optimum or range salinities, that result must be applied carefully to avoid being misled into considering that a given plan passes or fails the criteria of the Chatry salinities.

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[1] Personal communication from Burnell Thibodeaux, May 1996.

Plate 11 illustrates mean monthly salinities at node 1259 as predicted by Equation 7 for the 50 percent tributaries' flow and no diversion (base). The Chatry target salinities are also shown as optimum range and range limits. The comparable TABS-MD three-dimensional model results for April through August are displayed as data points to illustrate the agreement between model results and Equation 7. It can be seen that some months (e.g., January and February) are within the optimum salinity range without freshwater diversion, whereas most months' salinities are above or even well above (e.g., May) optimum levels.

Plate 12 provides the same information for the RT diversion plan. It shows that Plan RT reduces salinities, but they are above optimum target levels in April and May, bottoming out at about 10 ppt, and freshened below the optimum levels in June and August through January. April and May salinities are, however, within the Chatry range limits. (The following discussion interprets these results in light of the Equation 7 error estimates.)

Plate 13 shows Plan MBP5 results. It also falls above the April-May salinity optimum targets, getting only down to about 11 ppt in those months, but freshens to below optimum levels only in August-October. In every month except September, it achieves salinities within the range limits.

Plan LBC1 salinities for node 1259 are shown in Plate 14. Only numerical model results are plotted, since Equation 7 does not apply to any structural change in the system. It produces salinities at node 1259 very much like those generated by Plan MBP5 except that Lake Pontchartrain is freshened less by LBC1.

Equation 7 was used to calculate the discharges required to meet the target salinities. Calculations showed that the residual effect of diverted water will freshen the system below the Chatry optimum values throughout the summer if the very low target salinities of 6 to 9 ppt in April-May are achieved. By trial and error, two tentative schedules were generated: Plan NTE that attempted primarily to meet the early spring target salinities at the expense of freshening below optimum at other times in the year, and Plan NTO that sacrificed some of the desired April-May salinity reduction in order to maintain salinities with minimal deviation above or below the optimum range throughout the year. A third schedule, MBPJ, used the 8,500 cfs of Plan MBP5 and added 2,000 cfs in November but dropped flows in the other months.

Table 16 lists the monthly discharges for Plans NTE, NTO, and MBPJ (Plans RT and MBP5 are repeated for comparison); and Plates 15, 16, and 17 illustrate their respective effects on salinities at node 1259. Plan NTE can be seen to drop salinities to 8.2 and 8.0 ppt in April and May, respectively, both within the optimum range, freshen below optimum in January-March and June-September (below range limits in January, February, and June), and achieve the optimum target range in October-December. Plan NTO falls within the optimum range 8 months out of 12, and is within range limits in the other

Table 16 Plan NTE, NTO, and MBPJ Diversions, cfs					
Month	Plan RT	Plan MBP5	Plan NTE	Plan NTO	Plan MBPJ
Jan	1,000	4,000	22,400	1,000	0
Feb	6,000	8,500	27,400	20,000	0
Mar	20,000	8,500	32,400	25,000	8,500
Apr	20,000	8,500	34,468	25,000	8,500
May	0	0	30,000	0	0
Jun	5,000	6,000	0	0	0
Jul	6,000	8,500	0	0	0
Aug	3,000	5,300	0	0	0
Sep	7,000	3,800	0	0	0
Oct	8,150	0	3,000	5,000	0
Nov	5,000	0	1,500	0	2,000
Dec	0	0	0	1,000	0

4 months. Plan MBPJ salinities fall within optimum range 8 months and within range limits every month.

If the approximate 2 ppt freshening effect of Plan LBC1 can be assumed to be linearly superposed on Plan MBPJ, the low target salinities of April and May come within possible reach as illustrated in Plate 17. Note however, that such an addition of effects may err on the side of too much salinity reduction, since as observed elsewhere the salinity response at Line 2 is nonlinear, yielding diminishing salinity reduction for additional inputs of fresh water.

These results are for a single point on Line 2. A general idea of the salinity gradient in that vicinity can be obtained by examining the isohalines of Plates 6-10 and values of salinity at nearby nodes. In Plate 18 the Plan RT salinities for April-August at the other nodes can be seen to vary from substantially saltier than optimum (node 1501 on the south end of Line 2 during April-May) to substantially fresher (node 1392 to the west of Line 2 during June-August). This suggests that the zone of optimum salinities will be in the vicinity of but oriented somewhat differently from Line 2.

Discussion

The results presented here show the following:

a. The relationship between mean freshwater inputs and mean monthly salinities at a point in the Biloxi Marshes can be well defined by an expression such as Equation 2. Equation 7 reliably predicts TABS-MD three-dimensional model results at node 1259 for 50 percent exceedance tributary discharges and Bonnet Carré Diversions of up to 20,000 cfs. Above 20,000 cfs, Equation 7 is still useful, but its accuracy is uncertain. Comparison with other data from months outside the April-August experimental period suggests that the TABS model results, and thus Equation 7 results, will be improved by including a typical seasonal variation in Gulf mean water level.

b. The Pankow monthly lag weights of Equations 3 and 4 are consistent with the three-dimensional numerical model results and indicate that while the largest impact comes about 30 days after a change in flow, there are still cumulative effects from 90 to 120 days. Such cumulative effects will complicate operation of the diversion, since water released in one month will continue to contribute to reduced salinities for the following 4 months. (Note the exception cited for 1983 in Chapter 3.) That residual effect will require a project operational plan that accounts for the statistical variation of expected future natural riverflows.

c. The GDM finding that the location chosen to achieve the target salinities makes a significant difference in the required diversion flows is confirmed by these results. Also confirmed is that the design flow capacity of the structure, about 30,000 cfs, was a conservative capacity to ensure that the May target salinities could be achieved at Line 2. If the May targets are met at Line 2 by GDM-scale flows, the succeeding 2 months may be fresher than the Chatry optimum values.

d. Salinities at the southern end of Line 2 were significantly higher than at the center for no diversion and Plan RT. Reductions to salinities in that area may require measures beyond freshwater releases, such as those mentioned by CTH (1995) and mentioned in subparagraph *e*.

e. These results support the CTH suggestion that the Lake Borgne-MRGO connections make a major contribution to salinity of the basin. Totally closing them generated salinity reductions of about 2 ppt near Line 2, so some fraction of that reduction is probably attainable by applying some more limited measure of control to those outlets. Such a control could, in combination with Bonnet Carré diversions lower than those proposed in the original design, achieve or approach target salinities at or near Line 2. Control of the connections could range from rock or pile structures to simpler measures such as creation of dredged material sills and dams that are periodically replenished. Since the connections were represented schematically in the model, they should be evaluated in a revised model before a firm decision is made.

f. Other salinity reducing measures suggested by the CTH could be used in combination with Bonnet Carré diversions on the order of MBPJ and Lake Borgne connections control to achieve target salinities, including the following:

(1) Closing the IHNC at Seabrook or the MRGO south of Lake Borgne.

(2) Constructing a jetty and sill in Lake Pontchartrain at the end of the IHNC to trap higher salinity intrusions during periods of stratification.

(3) Artificial destratification of the MRGO by water or bubble curtains.

(4) Supplemental freshwater diversions into the IHNC-MRGO via or adjacent to the Mississippi River lock.

g. The plans of Table 16 are for design purposes, not operation of the diversion; however, a potential design for a Bonnet Carré diversion operational plan can be inferred from these results. The numerical model used here can be refined and reverified, then used to develop response functions (similar to Equation 7, but with additional independent variables such as mean Gulf level, etc.) to a range of tributary inflows and freshwater diversions. Those functions would then be employed in a gaming analysis (like those previously conducted by the New Orleans District) using historical observations to work backwards into a set of operations rules that will achieve target salinities on average over several years.

h. Since the error analysis of Equation 7 suggests that it may yield salinities that are too low for the late summer and fall months, the Plates 12, 13, and 15-17 predictions must be used with caution. The months for which the equation indicates overfreshening should be interpreted as having salinities lowered at least to Chatry optimum levels, since the degree of overfreshening is within the possible error band of that equation.

6 Conclusions and Recommendations

Tools

The three-dimensional TABS-MD numerical model has been verified to limited field data and is an appropriate tool to address the circulation and salinity questions posed in the objectives. It can be used in the future to devise an operational plan for the Bonnet Carré diversion structure. It should be improved by

a. Increasing mesh resolution around the MRGO-Lake Borgne connections to better define them and their flow characteristics.

b. Adding intra-annual Gulf mean water level fluctuations and possibly other subtidal frequency water level variations to the boundary conditions.

c. Verification to additional field data sets, including periods with greater tributaries' discharges and more field observations of salinities, particularly in the MRGO and IHNC.

d. Evaluation of the effect of daily discharge variations on salinity responses and suitable adjustment of boundary conditions.

Equation 7 is an accurate predictor of basin salinity response at the location of node 1259 in the Biloxi Marshes for April through July, typical tributary discharges, and Bonnet Carré diversions up to 20,000 cfs. It cannot be applied to structural changes such as the MRGO-Lake Borgne connections, although the form of the equation may still be valid. Equation 7 errors increase for the months of August through October and it is untested at higher freshwater flows, but it can still be used in those circumstances with proper care.

Lake Pontchartrain Basin Estuary Salinity Response

Basin salinities respond slowly to any change. Salinities in the Biloxi Marshes show a reduction due to Lake Pontchartrain freshwater diversions within the first 30 days, show maximum effects at about 60 days, then demonstrate a declining but noticeable effect for at least 120 days.

The basin's slow response and persistence of fresh water in the system mean that it may be physically impossible for average monthly salinities in any single year to fall within the Chatry optimum limits for every month in that year. For example, if natural conditions caused salinity at node 1259 to average 7 ppt in a typical May, the June average salinity would probably be lower than the optimum 12.5 ppt. That conclusion applies whether a diversion project exists or not.

Salinities at Line 2 respond to freshwater flows nonlinearly, in that each succeeding salinity decrease requires more Lake Pontchartrain freshwater contribution than the preceding decrease required. The salinity response contours can be visualized as a mechanical spring's coils, which are easy to compress at first, but require progressively more force to continue compressing.

Plan LBC1 results confirm a significant role of the MRGO in the salinity regime of the basin, including Lake Pontchartrain. The Lake Borgne connections contribute to about 2 ppt of the salinity at node 1259 on average.

Plan Effects

The Bonnet Carré Diversion GDM design with maximum flow of about 30,000 cfs could achieve an average monthly salinity at Line 2 that is within the Chatry optimum range in a typical May.

Any diversion into Lake Pontchartrain that can achieve the Chatry optimum range in May will probably result in salinities at Line 2 being fresher than optimum in June for the same reason as given in the conclusions in the preceding section.

The plans considered here will reduce salinities at Line 2 in the Biloxi Marshes for a typical year (50 percent exceedance flows.) Specifically, compared to the base, or no diversion, condition, the plans had the following effects on salinities at about the center of Line 2:

a. Plan RT (up to 20,000 cfs) reduced salinities up to 4.2 ppt during April-August. It reduced salinities to Chatry optimum values or less 10 months out of 12.

b. Plan MBP5 (up to 8,500 cfs) reduced salinities up to 3.4 ppt during April-August. It reduced salinities to Chatry optimum values or less 9 months out of 12.

c. Plan LBC1 (total closure of Lake Borgne-MRGO connections) reduced salinities up to about 2 ppt during April-August.

Other potential diversion schedules (e.g., NTO, NTE, and MBPJ) can be devised and salinity reduction evaluated by Equation 7 without model experimentation in order to balance achievement of salinity goals with other criteria. Any plan should be subjected to model experimentation before design is complete and before an operational plan is designed.

Control of salt flux up MRGO and through the outlets may contribute significantly to achieving Biloxi Marsh salinity goals. Possible control methods are discussed in the previous section. By extension, it may be possible to combine controls on MRGO salt contributions with smaller diversions (e.g., MBPJ) to approach target salinities at Line 2.

Operations Plan

The conclusions in "Lake Pontchartrain Basin Estuary Salinity Response" imply that a Bonnet Carré diversion schedule must be statistically based. The plans reported here must be replaced with a diversion operational plan that takes into account antecedent conditions and a stochastic forecast of future tributary inflows. Such an operational plan will produce some years fresher than desired and some years saltier than desired, as described in the GDM. The discussion section of this report suggests an approach for developing such an operational plan.

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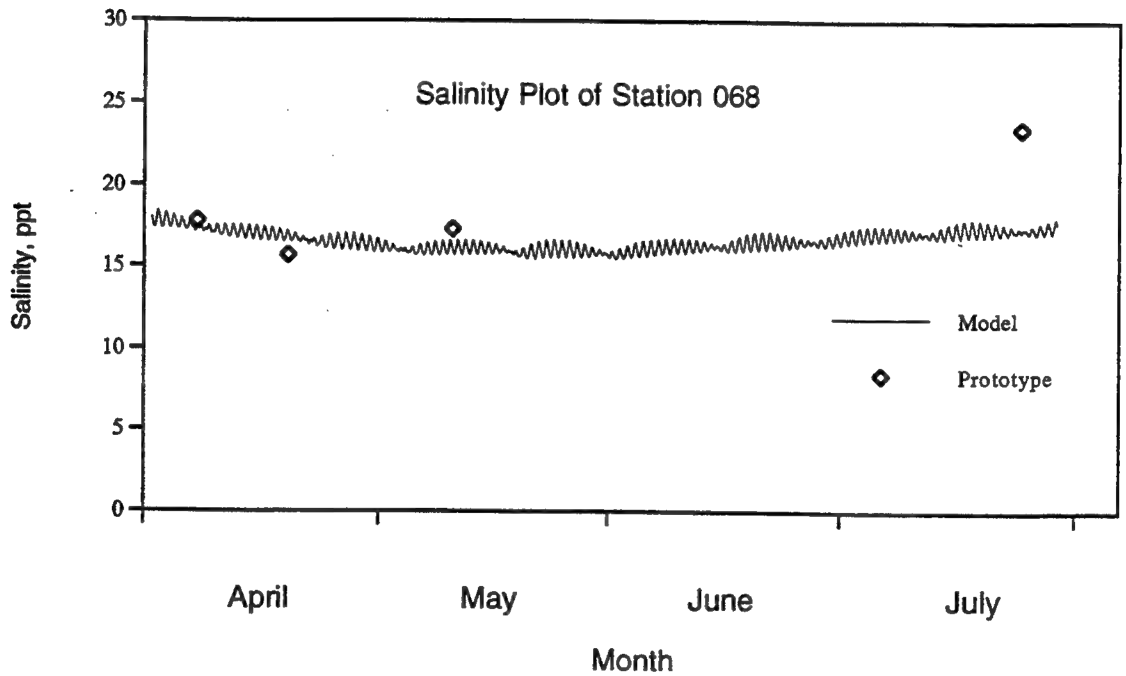
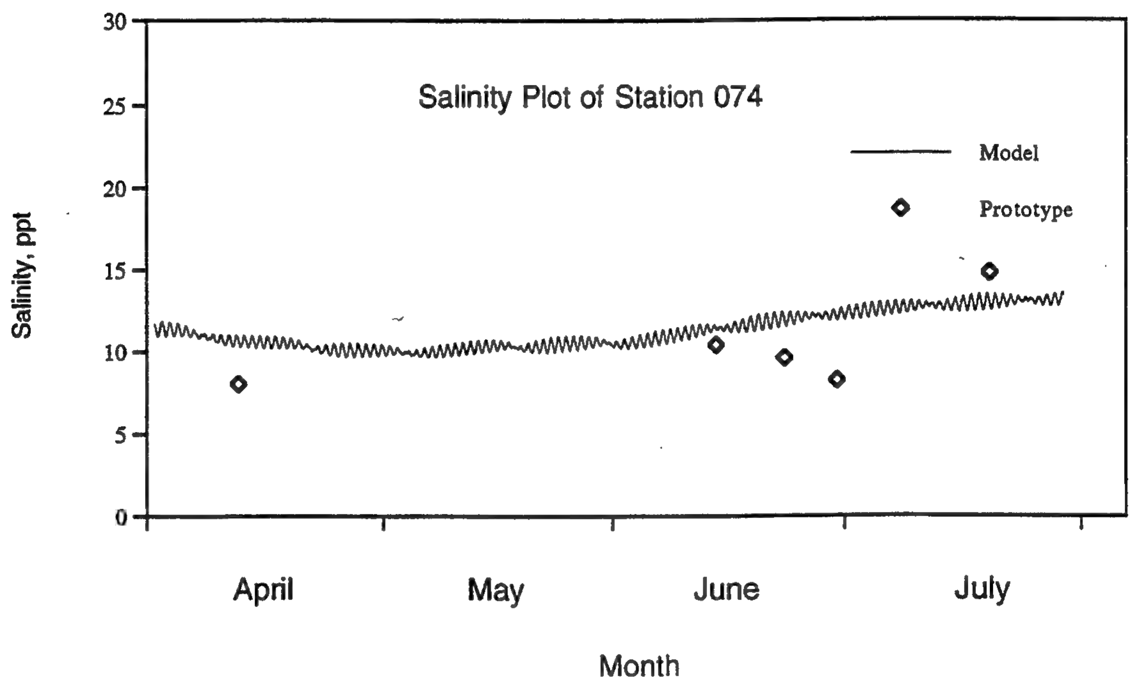


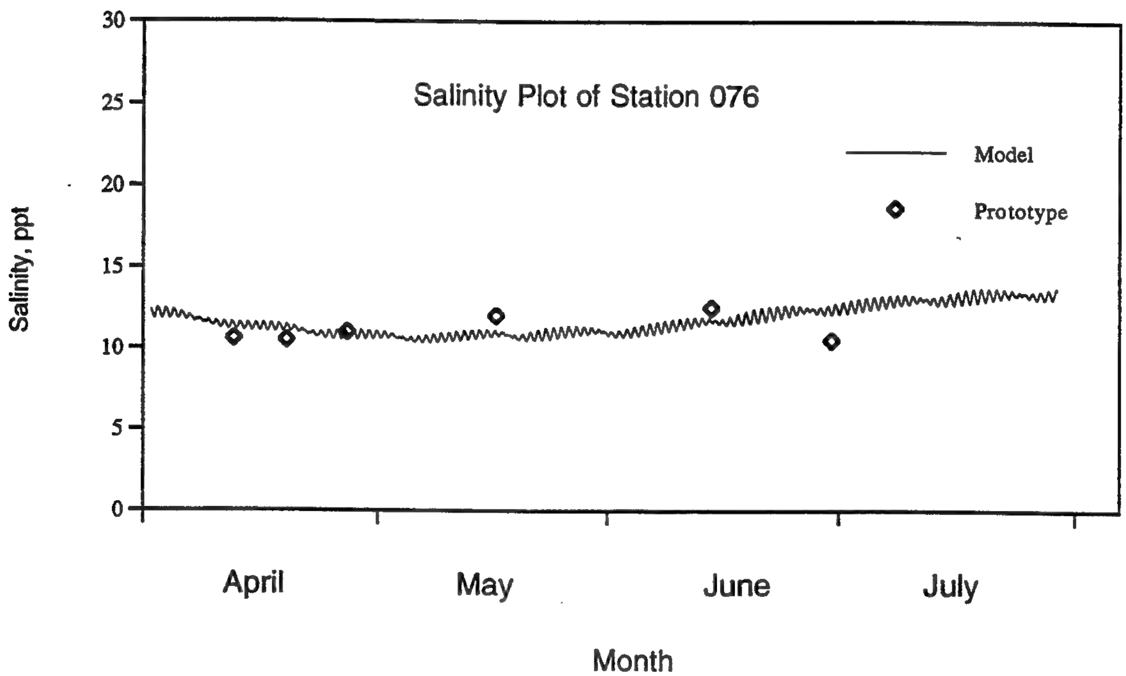
Salinity Verification
Station 068

Plate 1

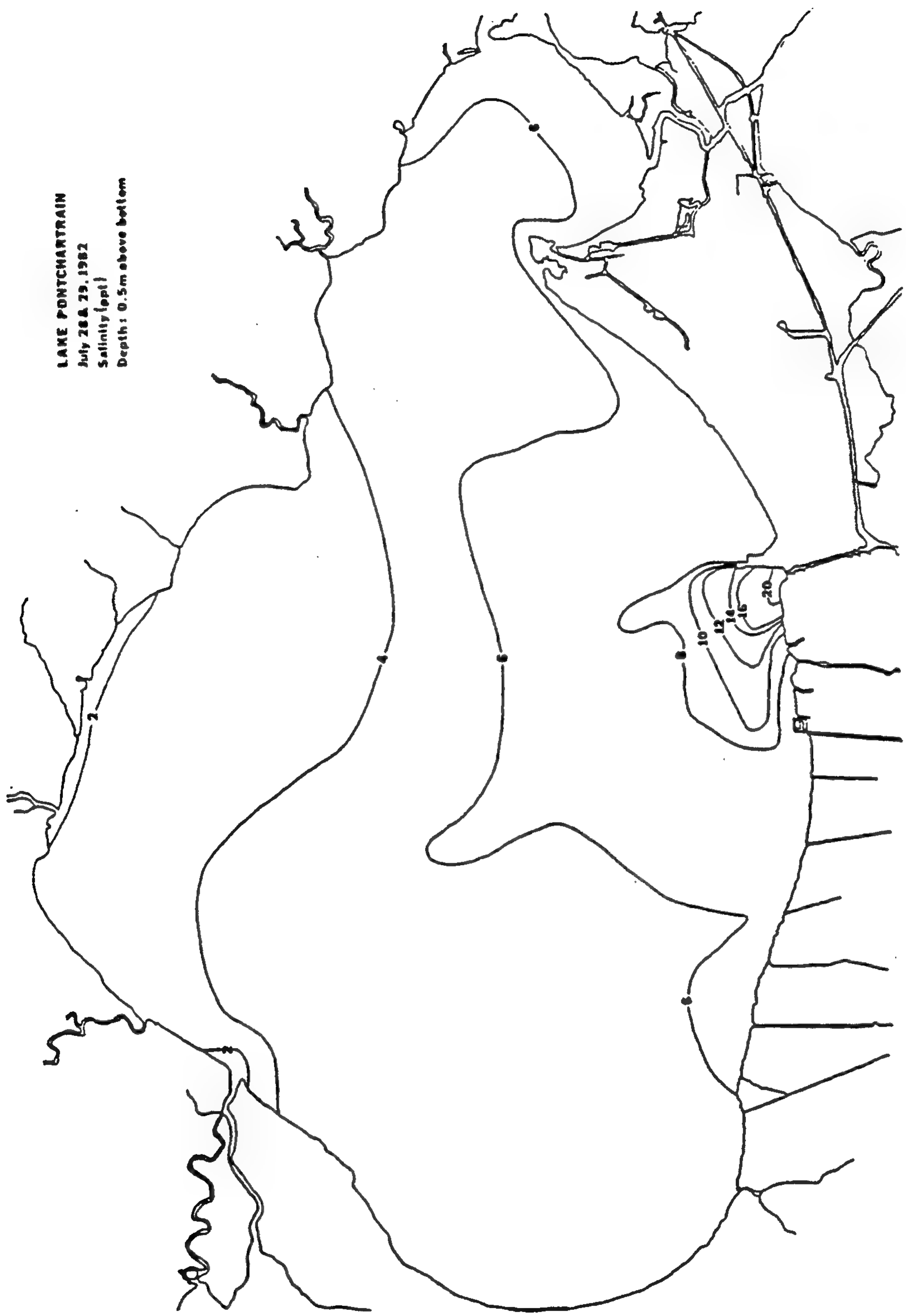


Salinity Verification
Station 074

Plate 2



Salinity Verification
Station 076



Lake Pontchartrain
Observed Near-bed Isohalines
July 28-29, 1982 (Schurtz and St. Pe 1982)

Plate 4
(Sheet 1 of 2)

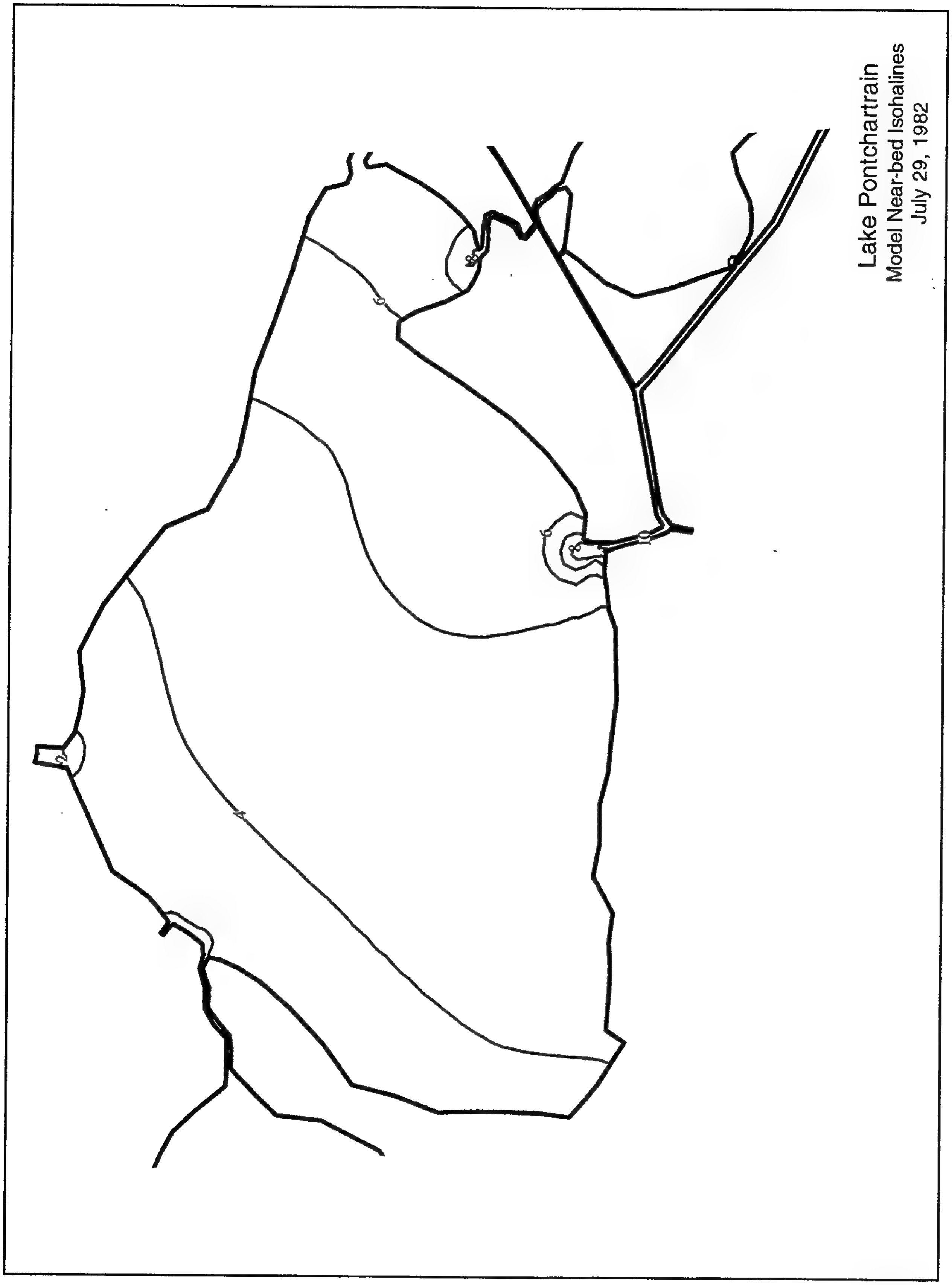
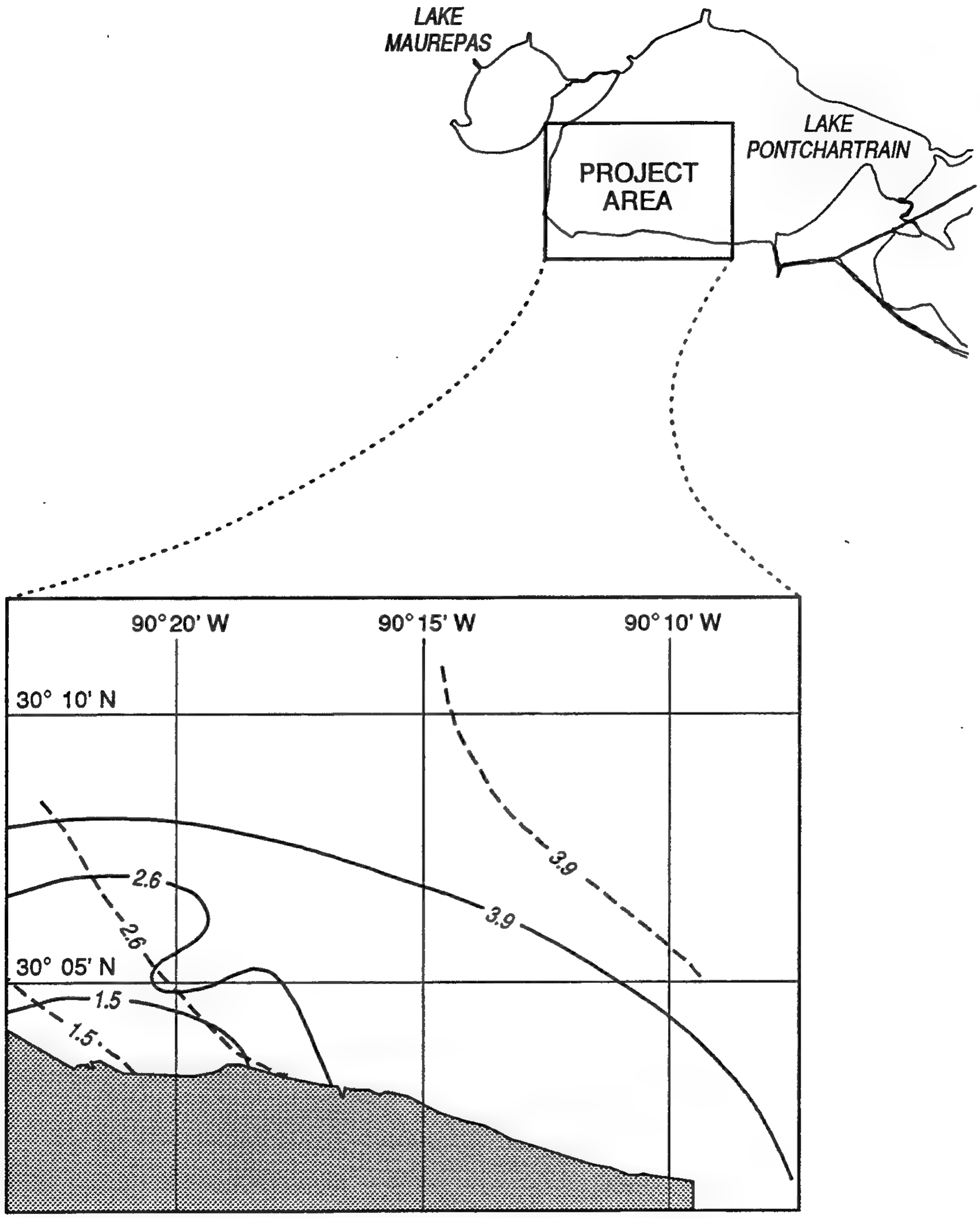
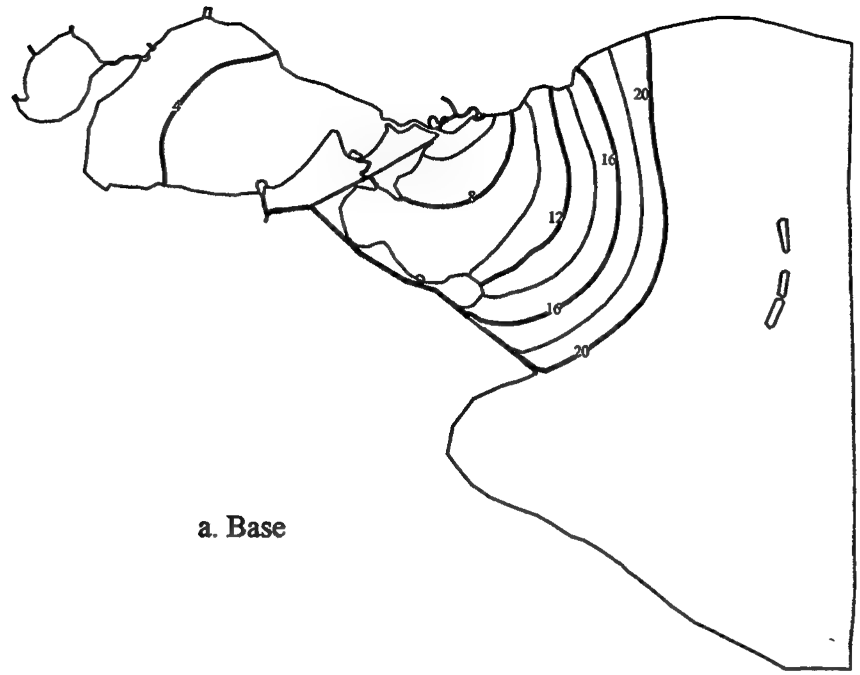


Plate 4
(Sheet 2 of 2)

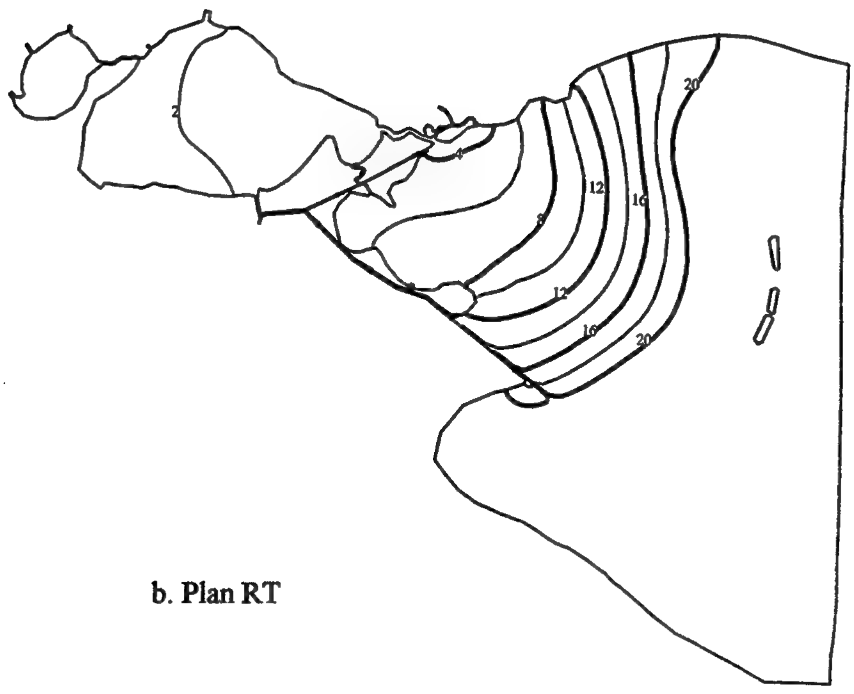


Lake Pontchartrain
Model (dashed lines) and Observed (solid lines)
May 27, 1994

Plate 5

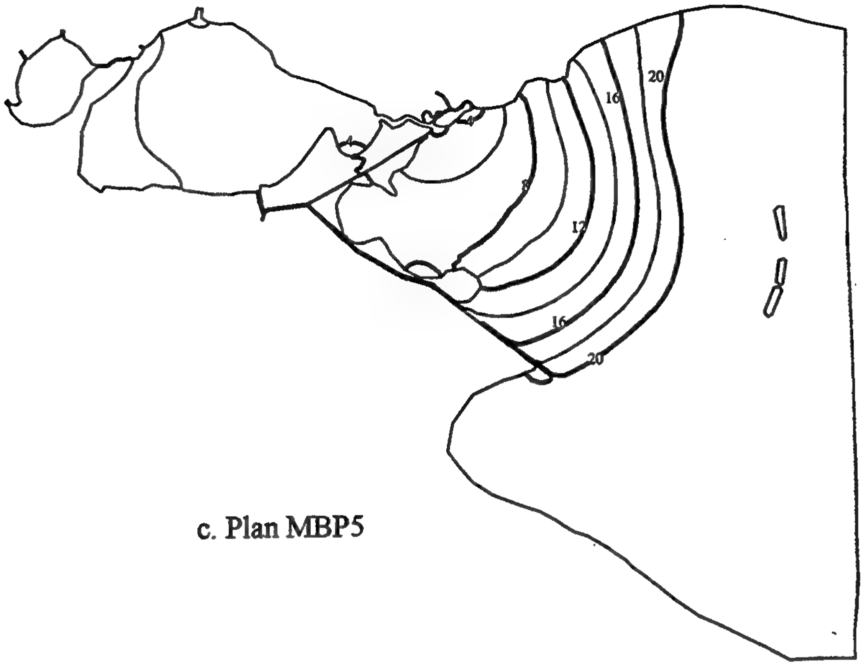


a. Base

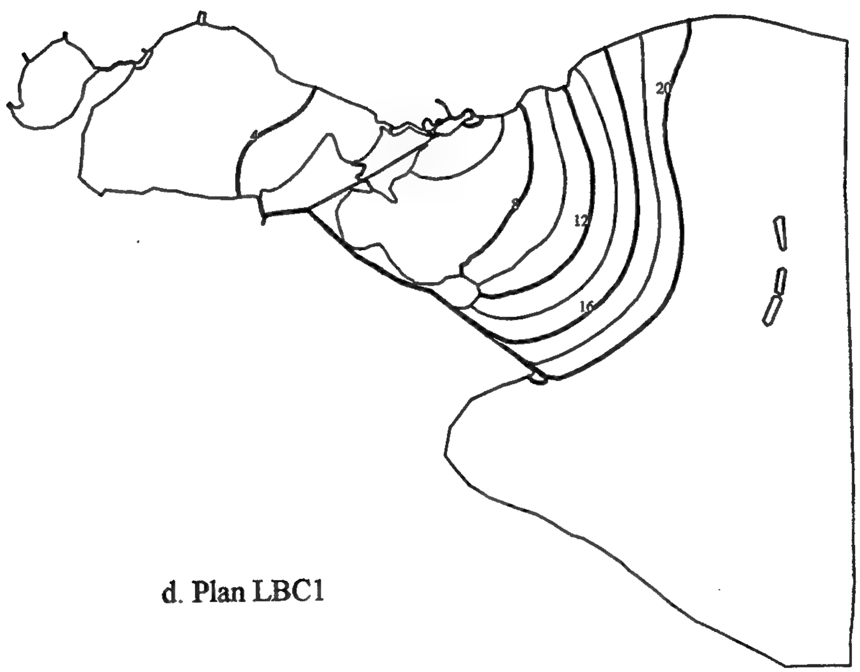


b. Plan RT

Pontchartrain Basin Isohalines
Base and Plans
April



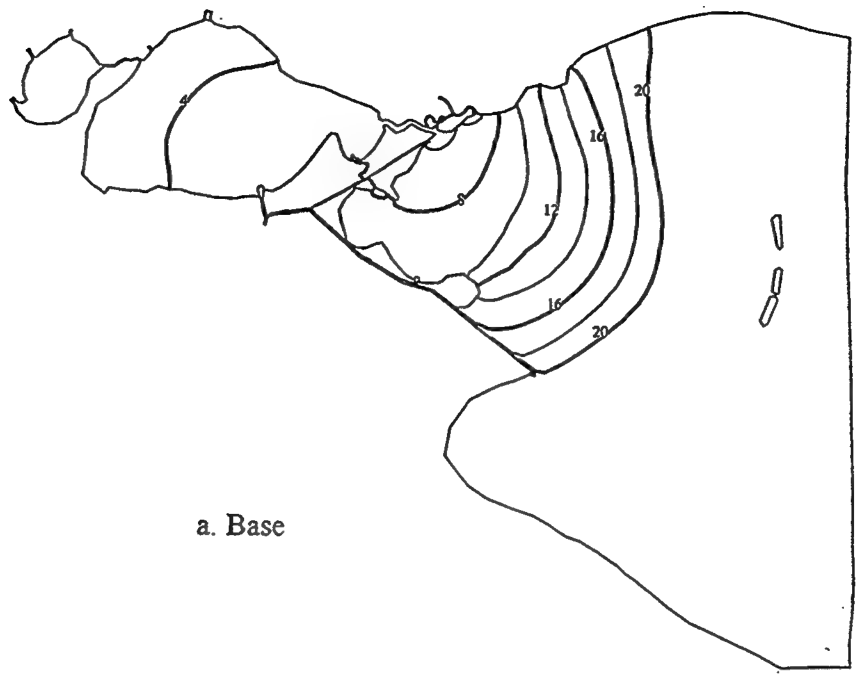
c. Plan MBP5



d. Plan LBC1

Pontchartrain Basin Isohalines
Base and Plans
April

Plate 6
(Sheet 2 of 2)



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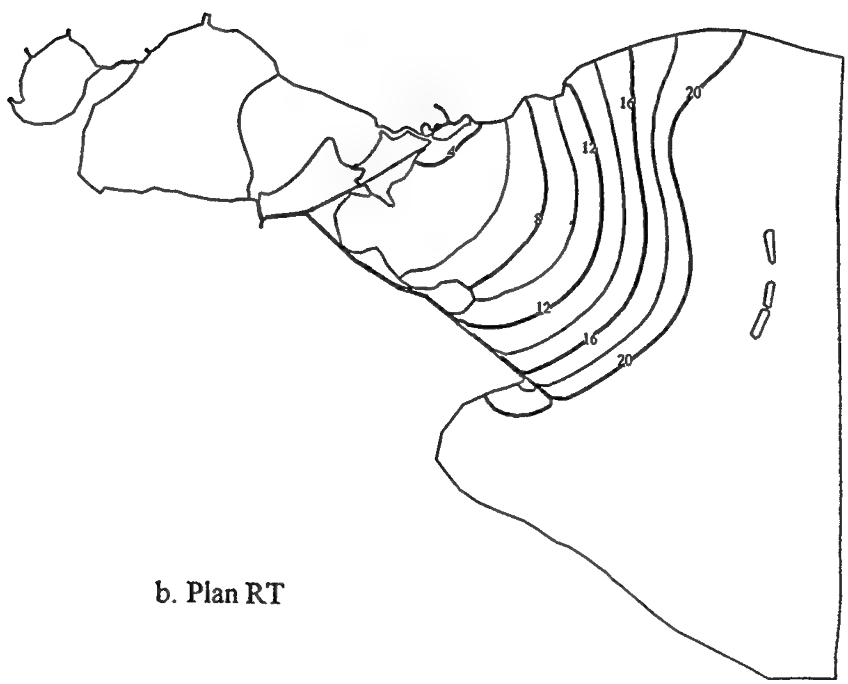
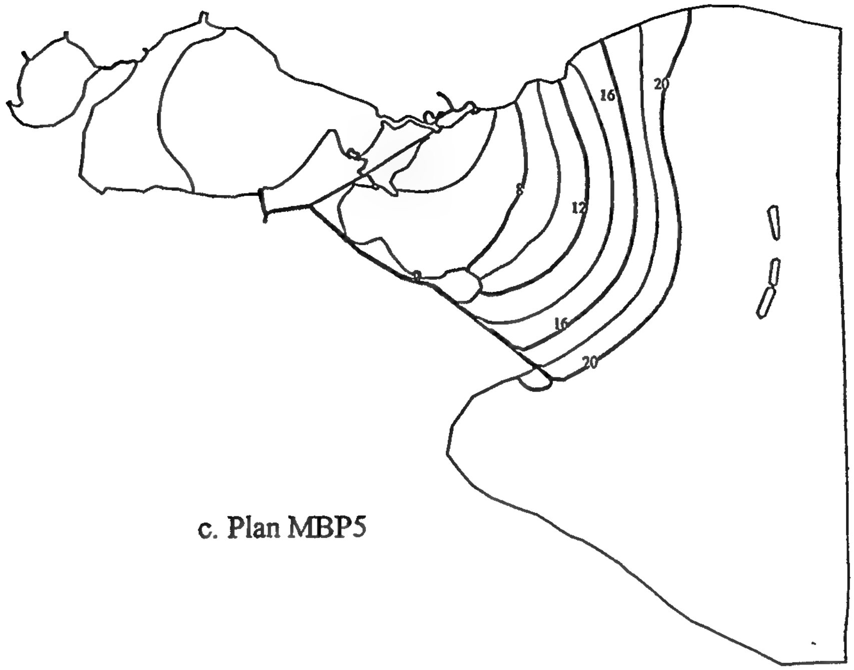
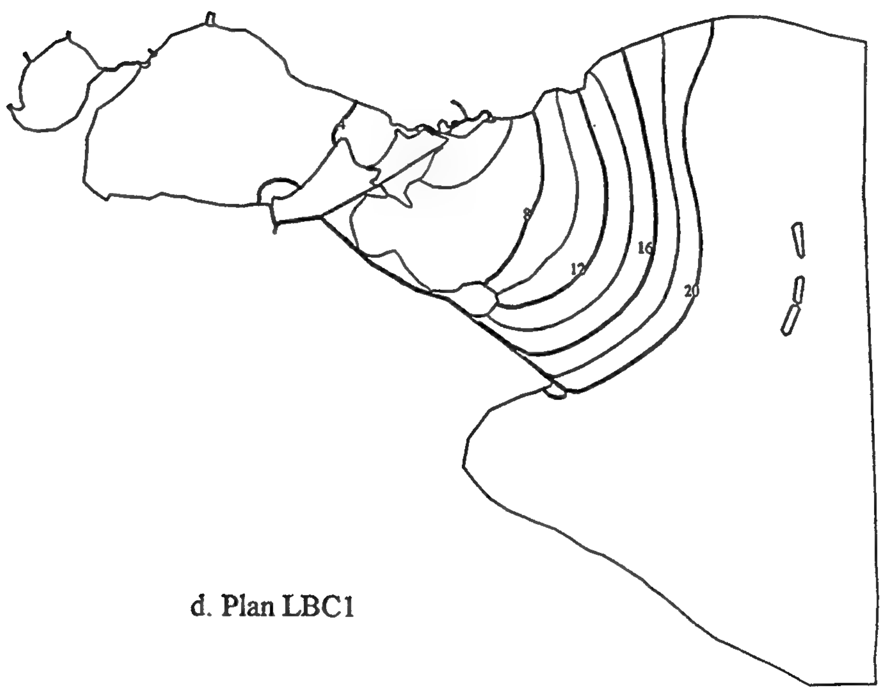


b. Plan RT

Pontchartrain Basin Isohalines
Base and Plans
May



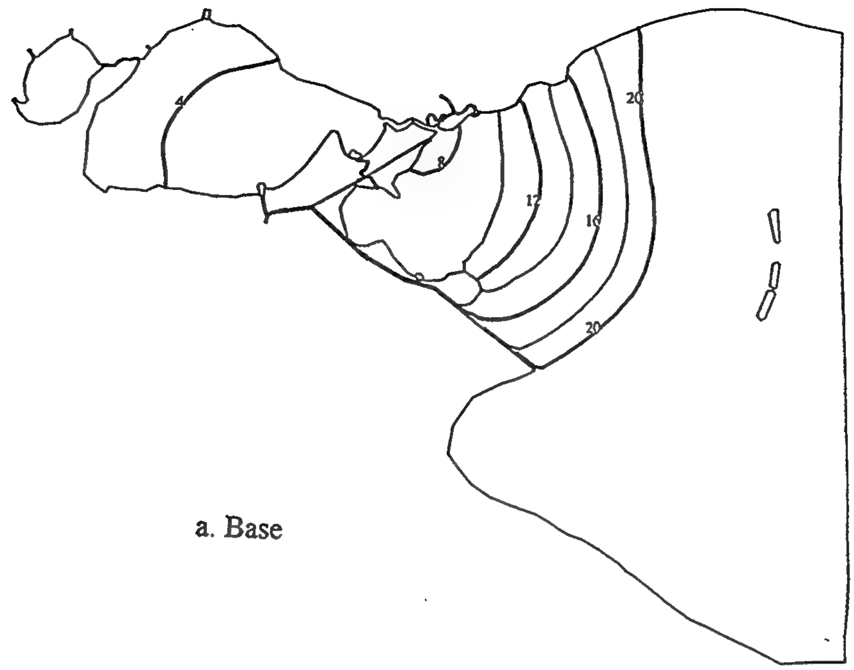
c. Plan MBP5



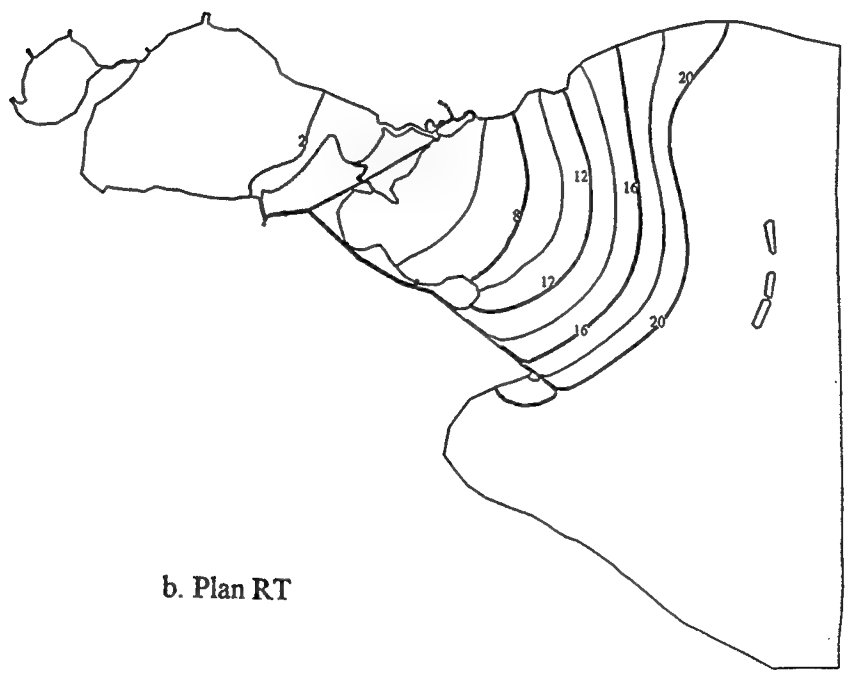
d. Plan LBC1

Pontchartrain Basin Isohalines
Base and Plans
May

Plate 7
(Sheet 2 of 2)

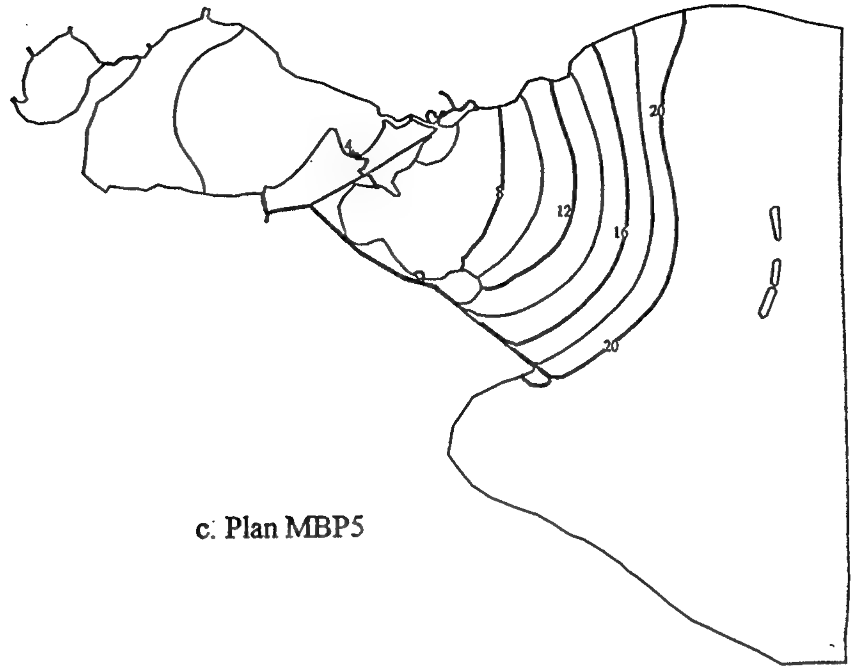


a. Base

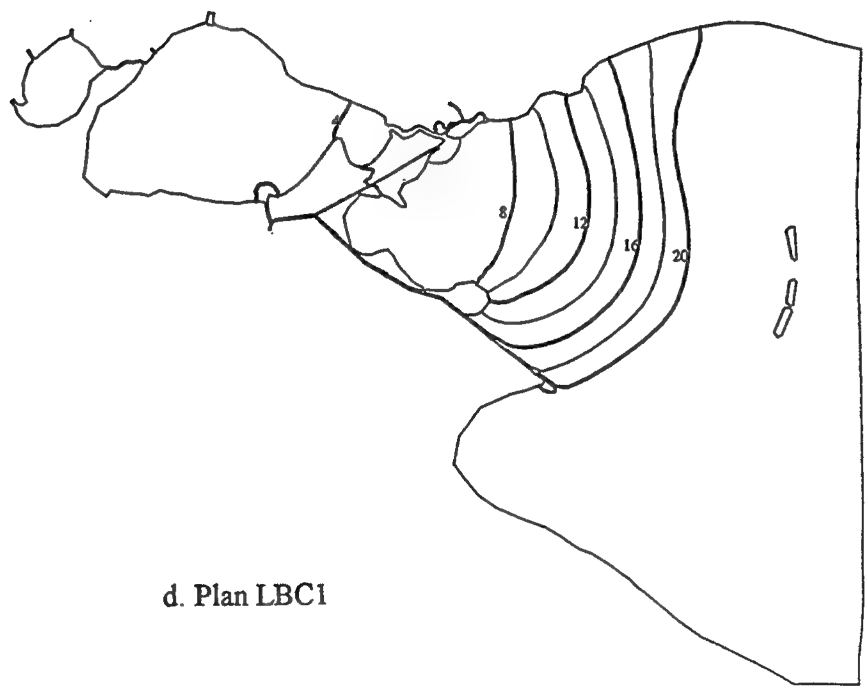


b. Plan RT

Pontchartrain Basin Isohalines
Base and Plans
June



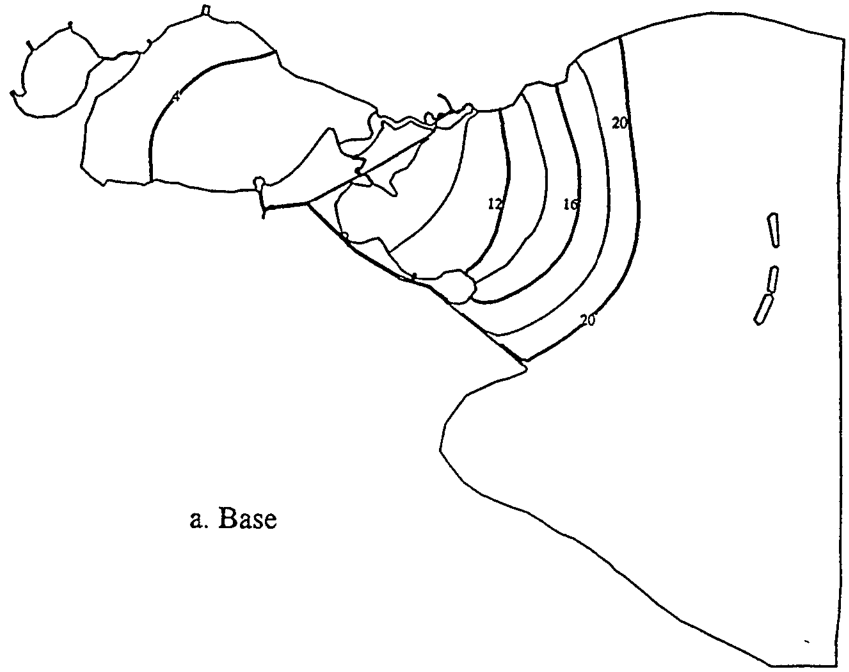
c. Plan MBP5



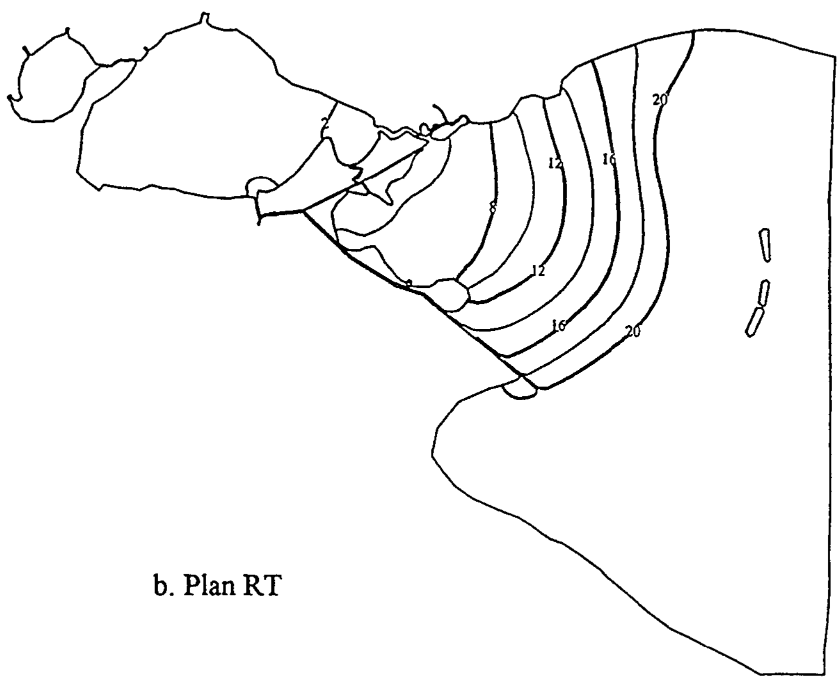
d. Plan LBC1

Pontchartrain Basin Isohalines
Base and Plans
June

Plate 8
(Sheet 2 of 2)

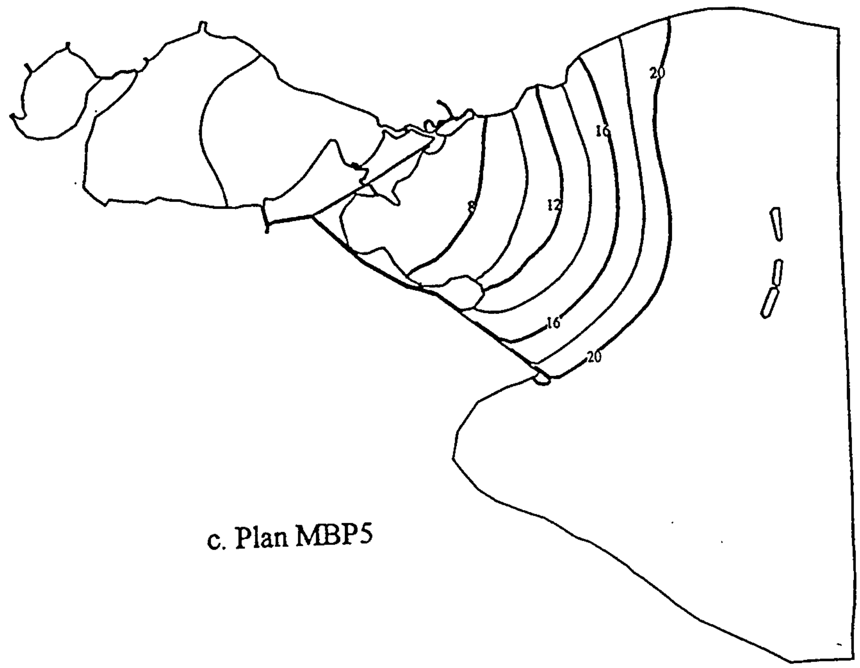


a. Base

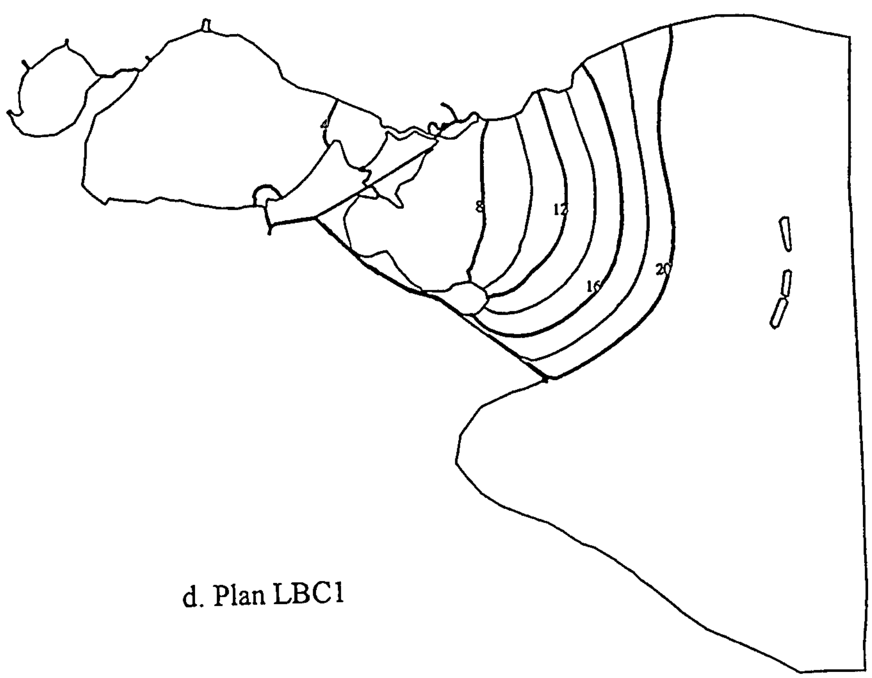


b. Plan RT

Pontchartrain Basin Isohalines
Base and Plans
July



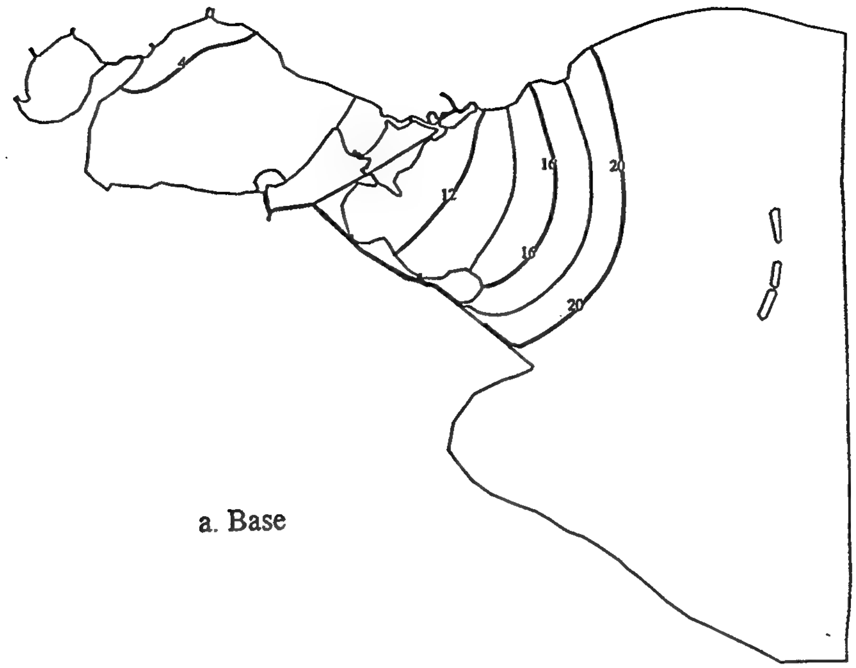
c. Plan MBP5



d. Plan LBC1

Pontchartrain Basin Isohalines
Base and Plans
July

Plate 9
(Sheet 2 of 2)



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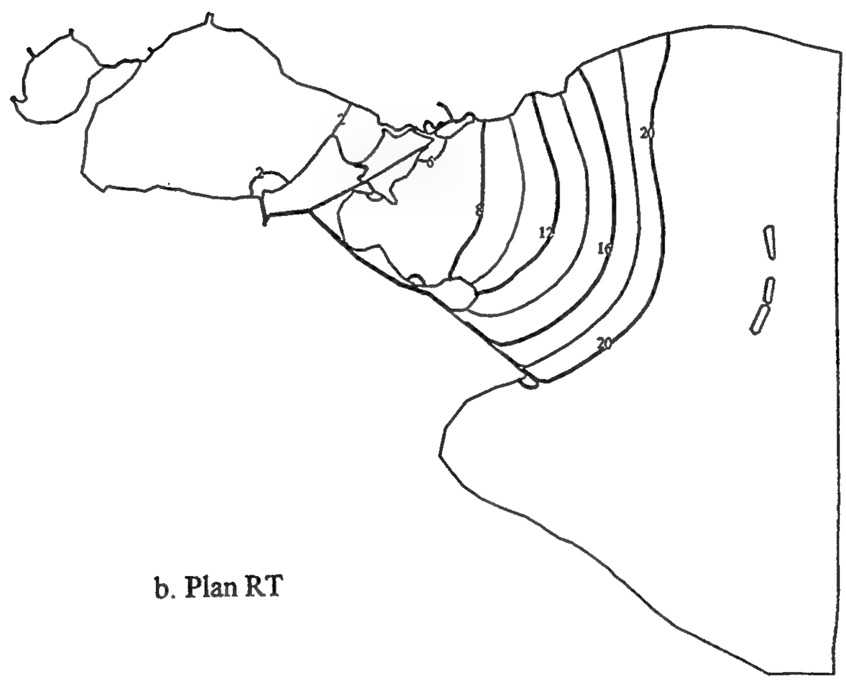
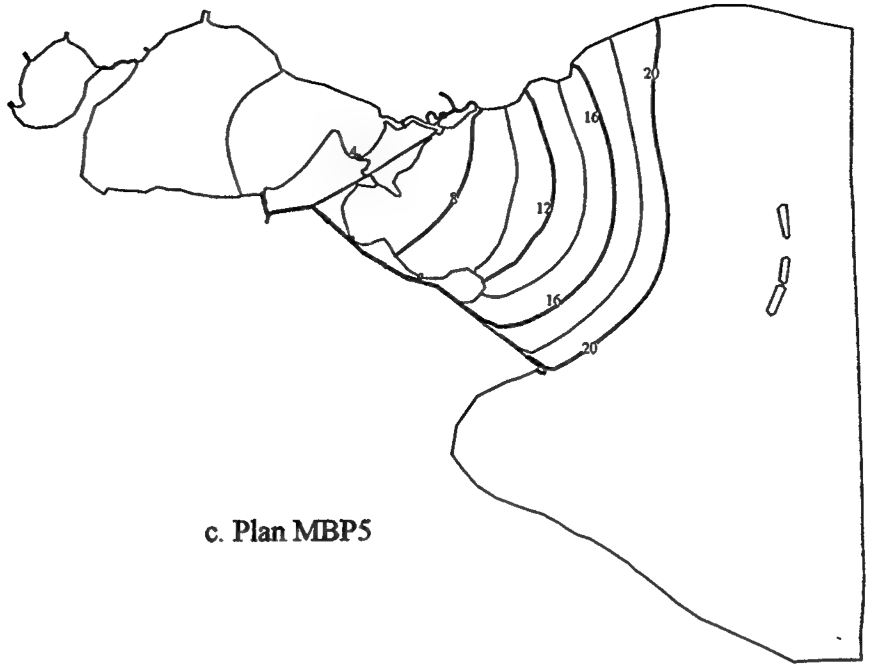
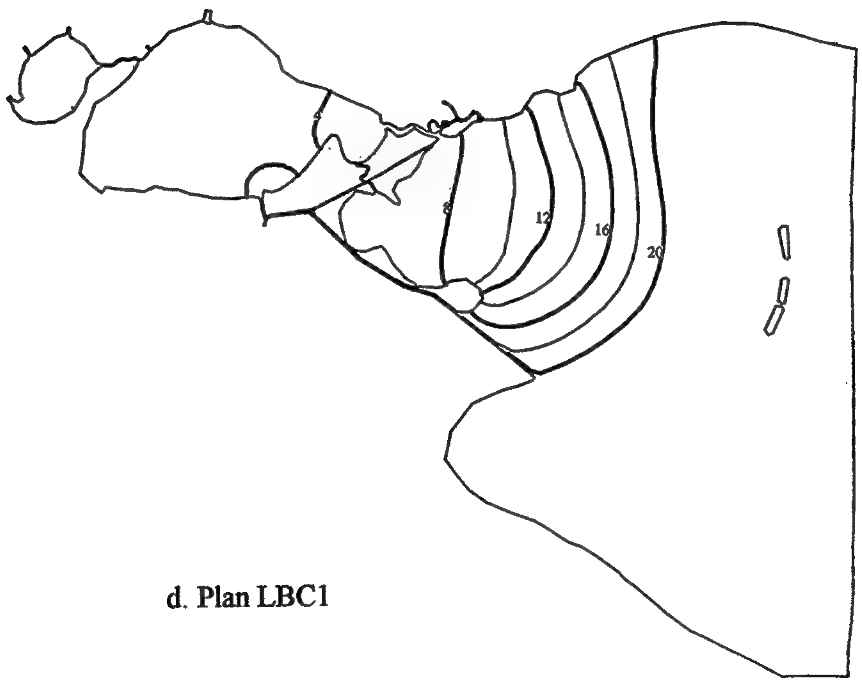


b. Plan RT

Pontchartrain Basin Isohalines
Base and Plans
August



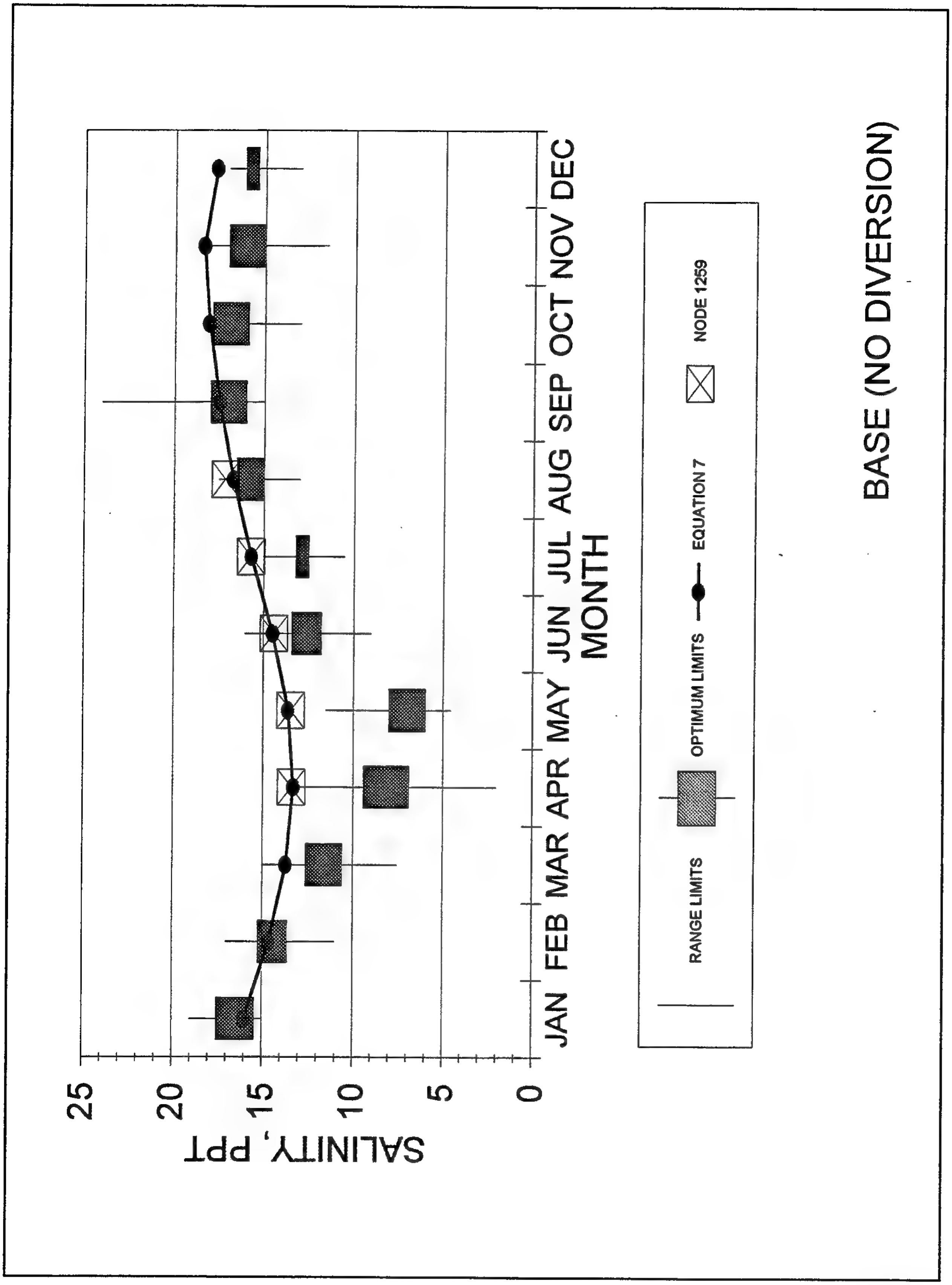
c. Plan MBP5



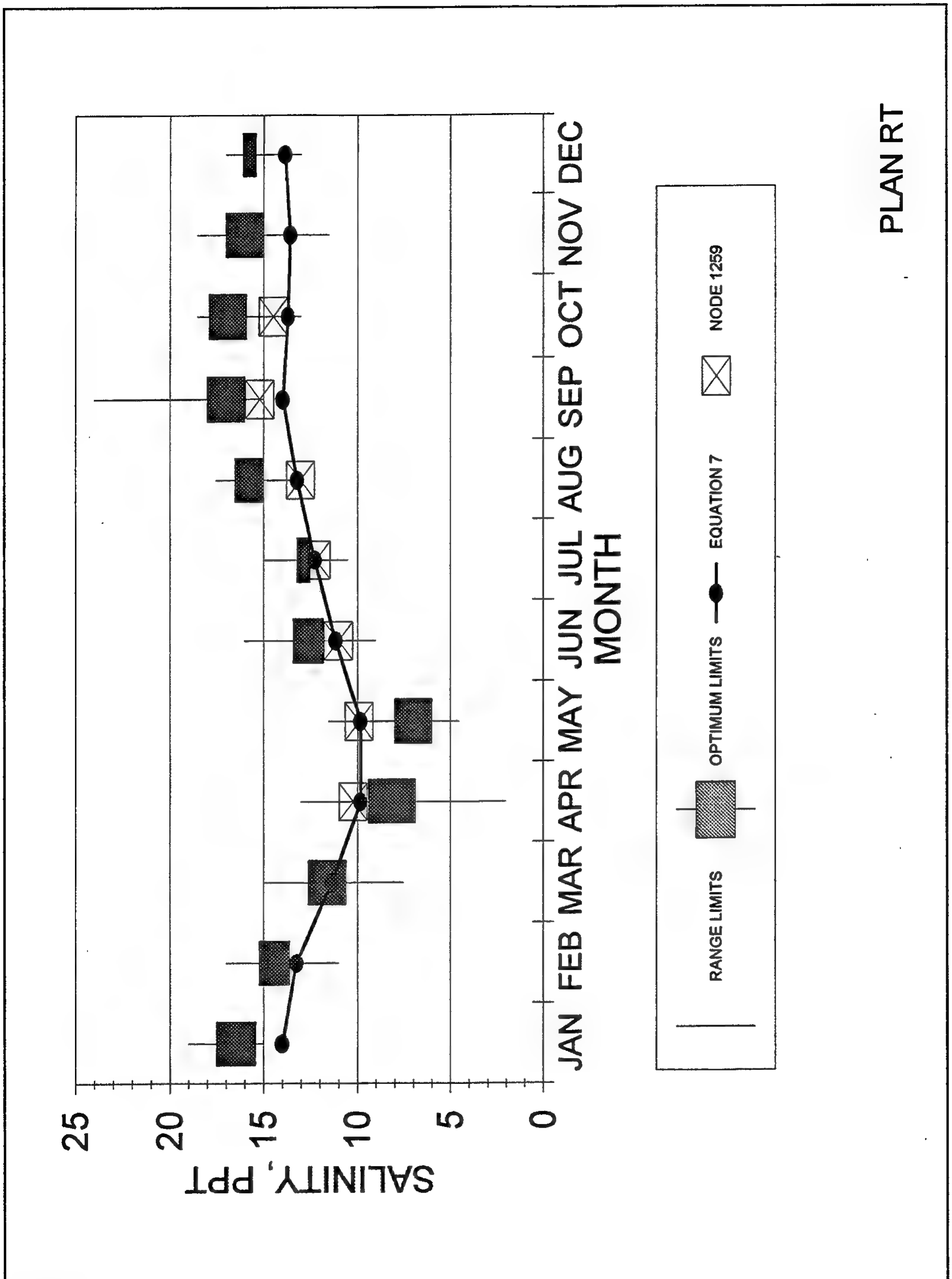
d. Plan LBC1

Pontchartrain Basin Isohalines
Base and Plans
August

Plate 10
(Sheet 2 of 2)



SALINITY, PPT
25
20
15
10
5
0
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
NODE 1259
BASE (NO DIVERSION)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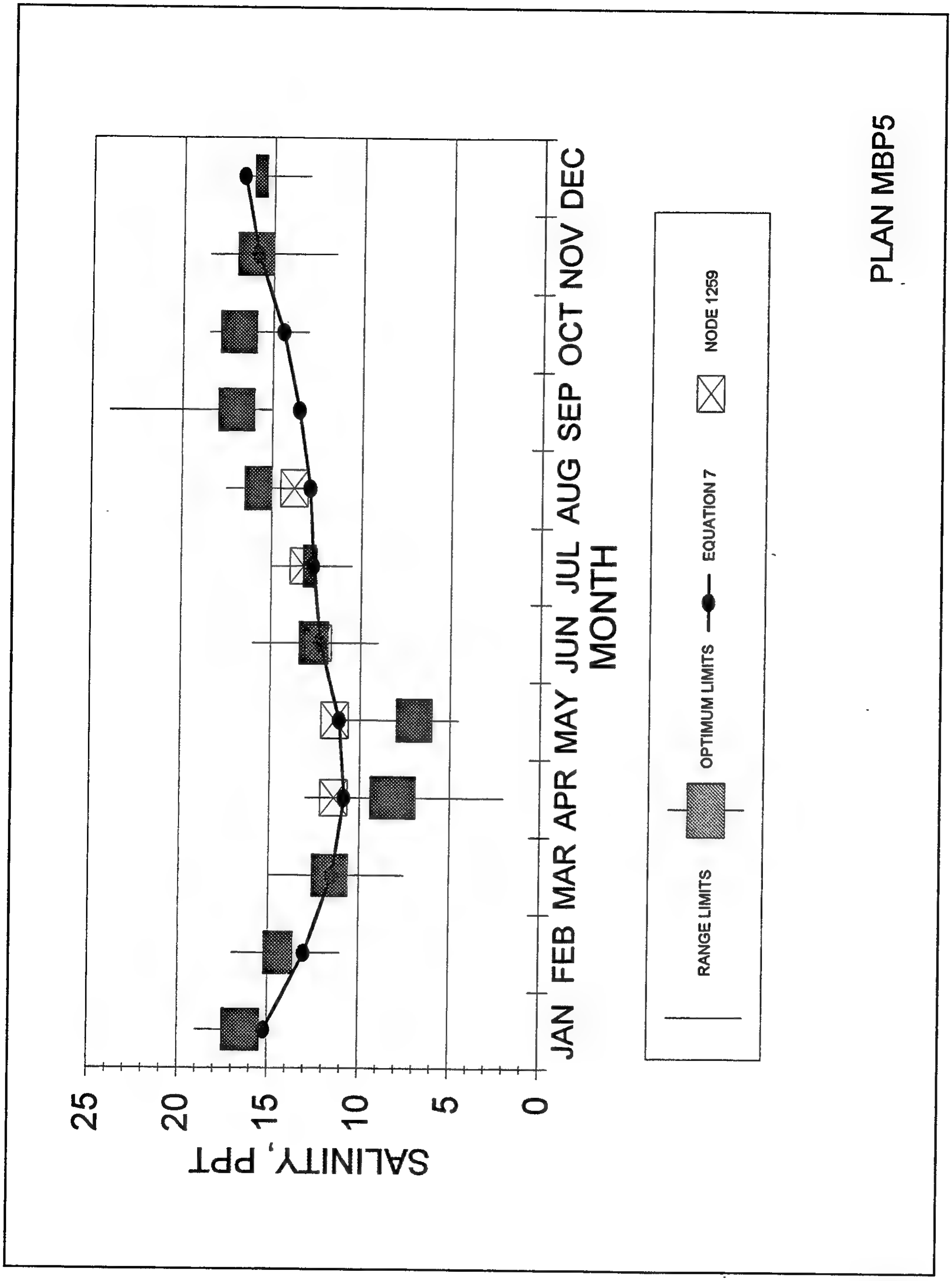
25
20
15
10
5
0
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
NODE 1259
PLAN RT

Plate 12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5
10
15
20
25
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
NODE 1259
PLAN MBP5

Plate 13

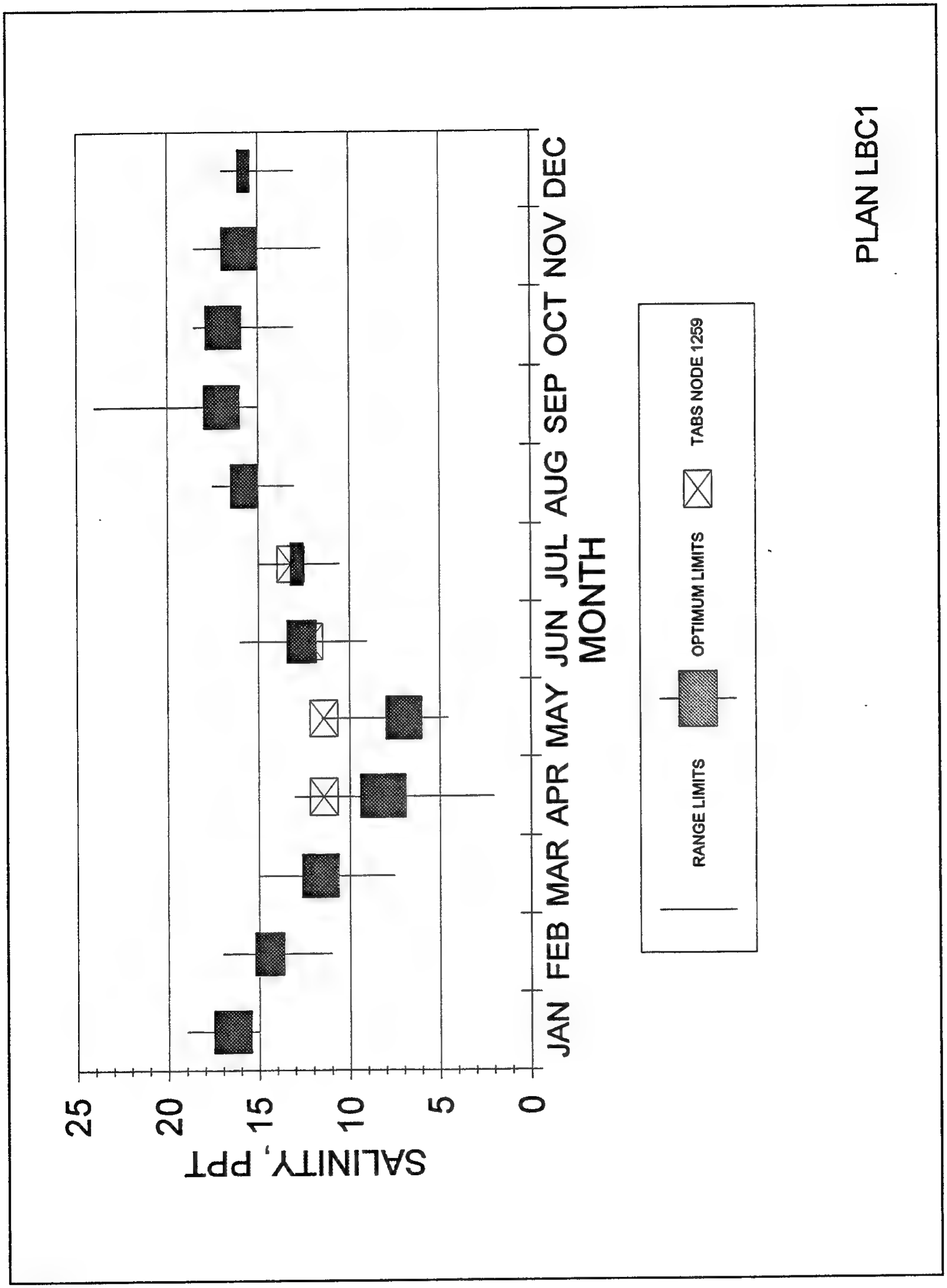
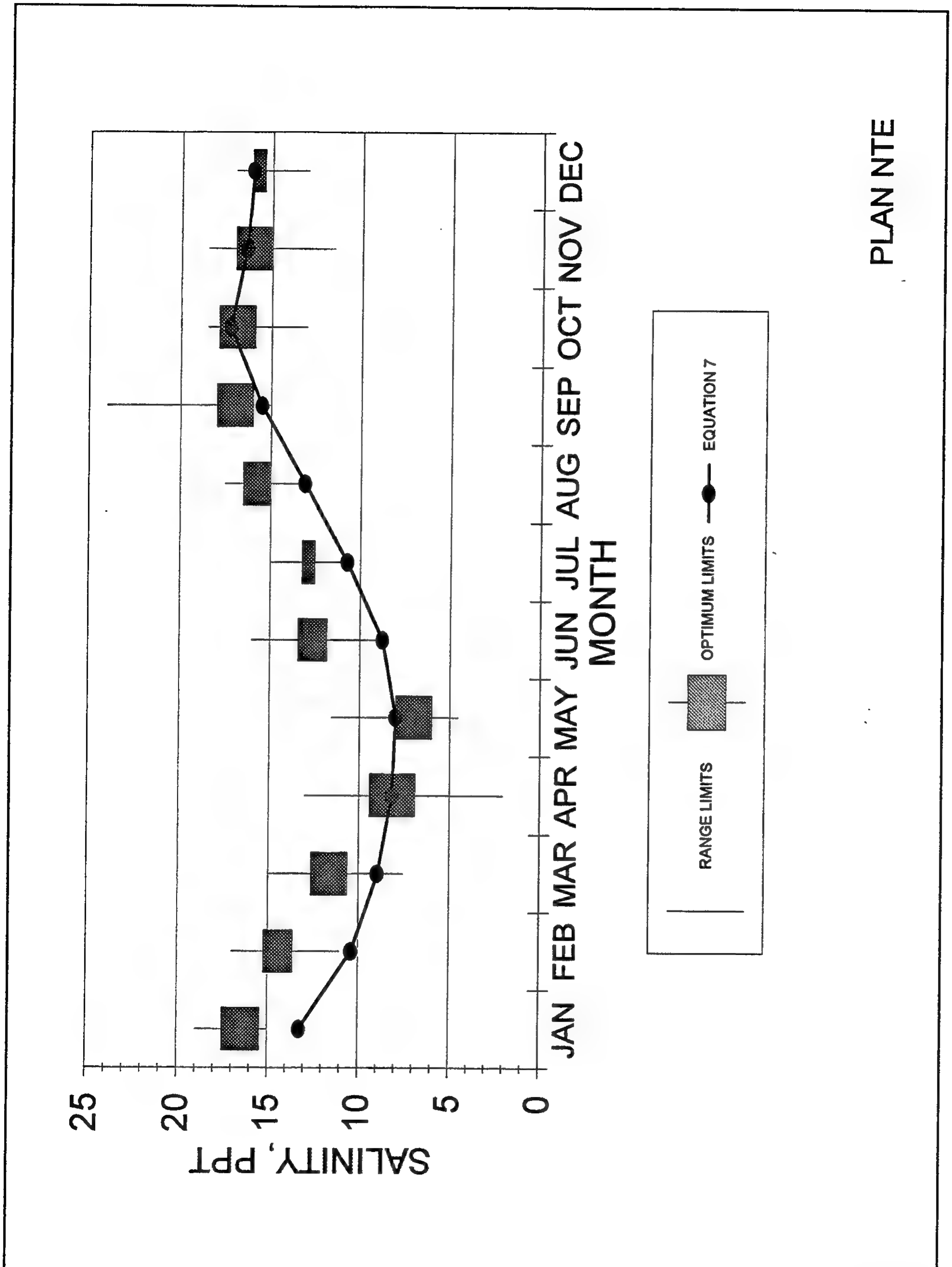
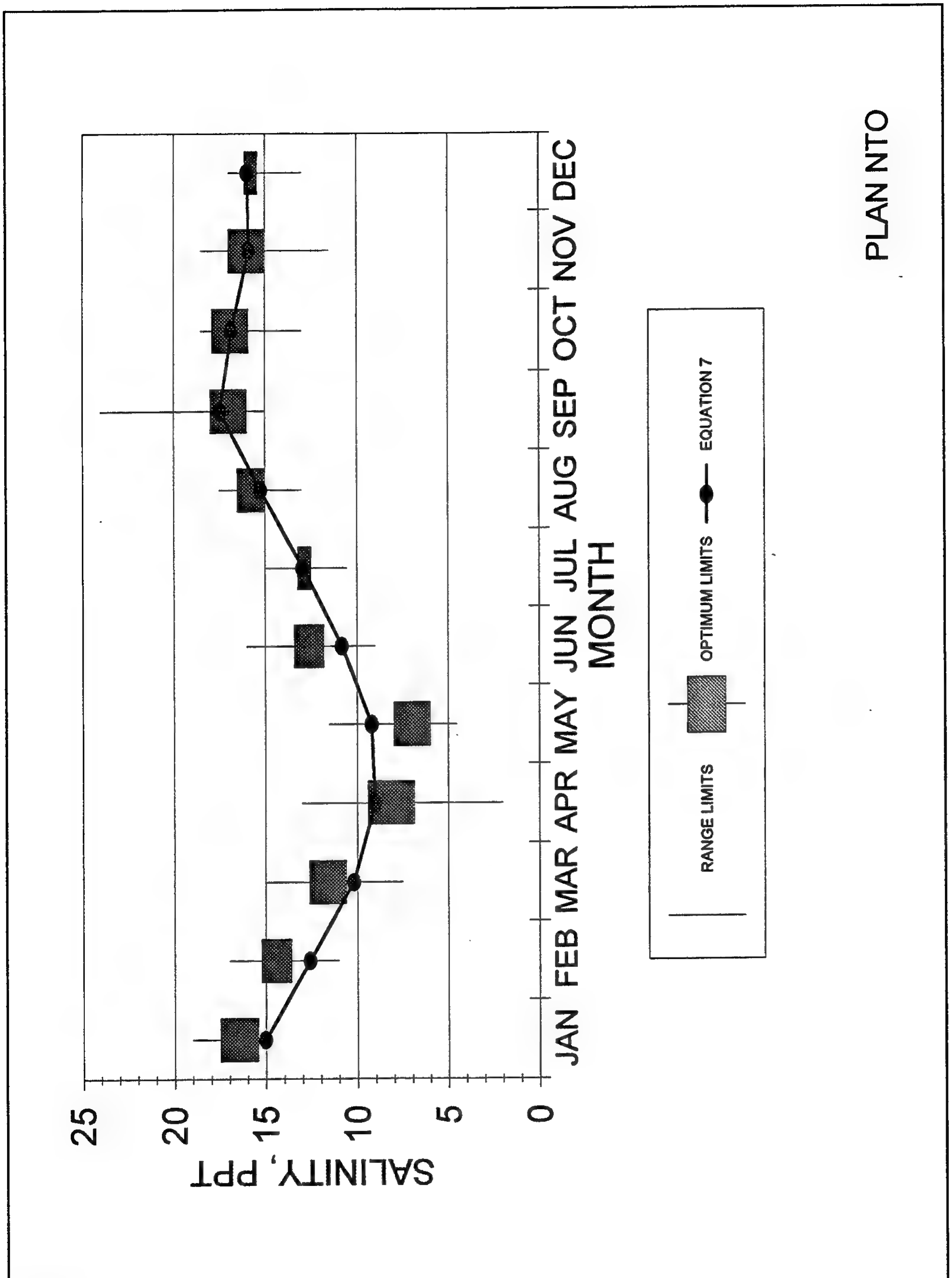

PLAN LBC1
SALINITY, PPT
0
5
10
15
20
25
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
TABS NODE 1259

Plate 14


SALINITY, PPT
0
5
10
15
20
25
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
PLAN NTE


SALINITY, PPT
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20
15
10
5
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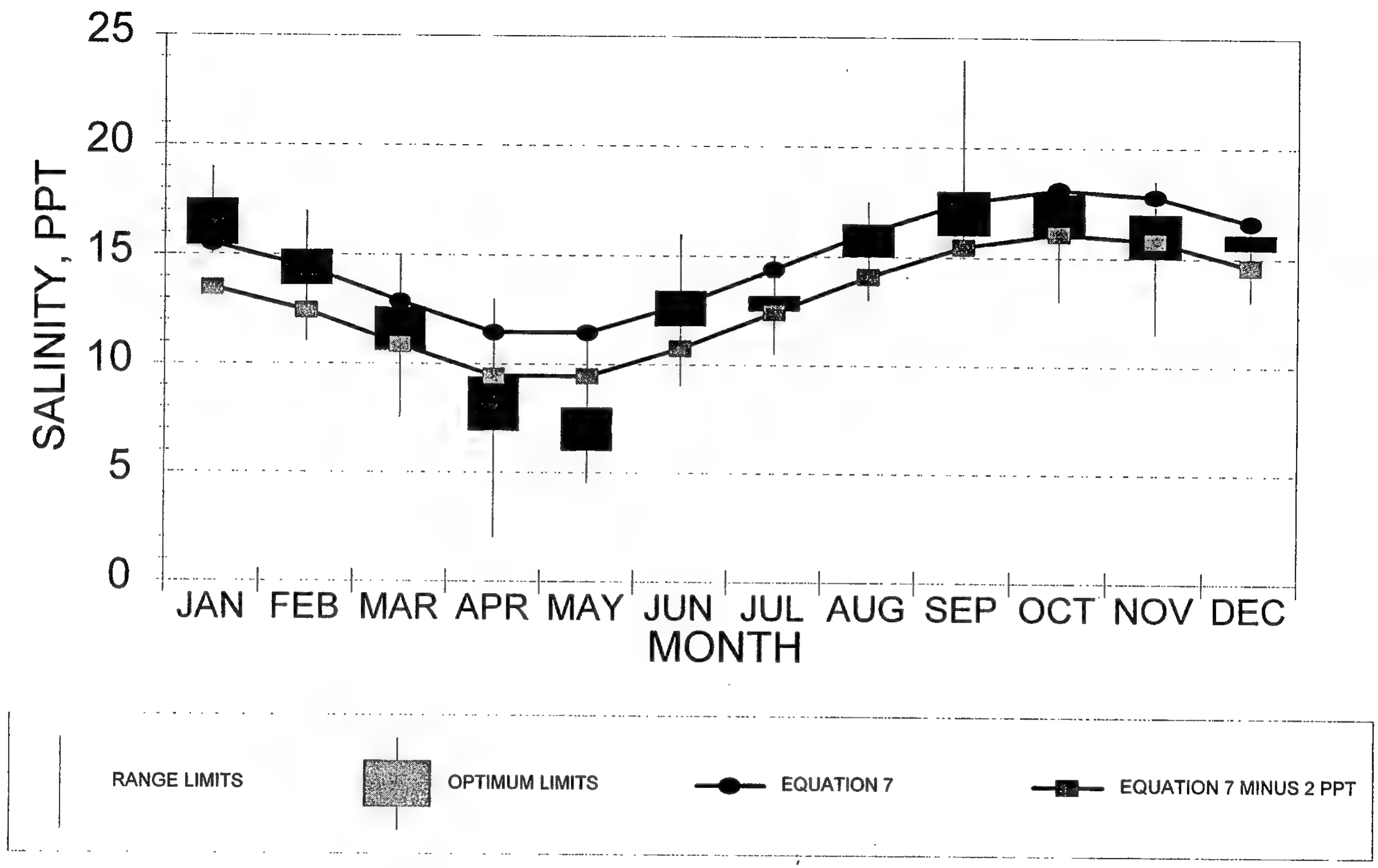
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
PLAN NTO

Plate 16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5
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SALINITY, PPT
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
RANGE LIMITS
OPTIMUM LIMITS
EQUATION 7
EQUATION 7 MINUS 2 PPT

PLAN MBPJ

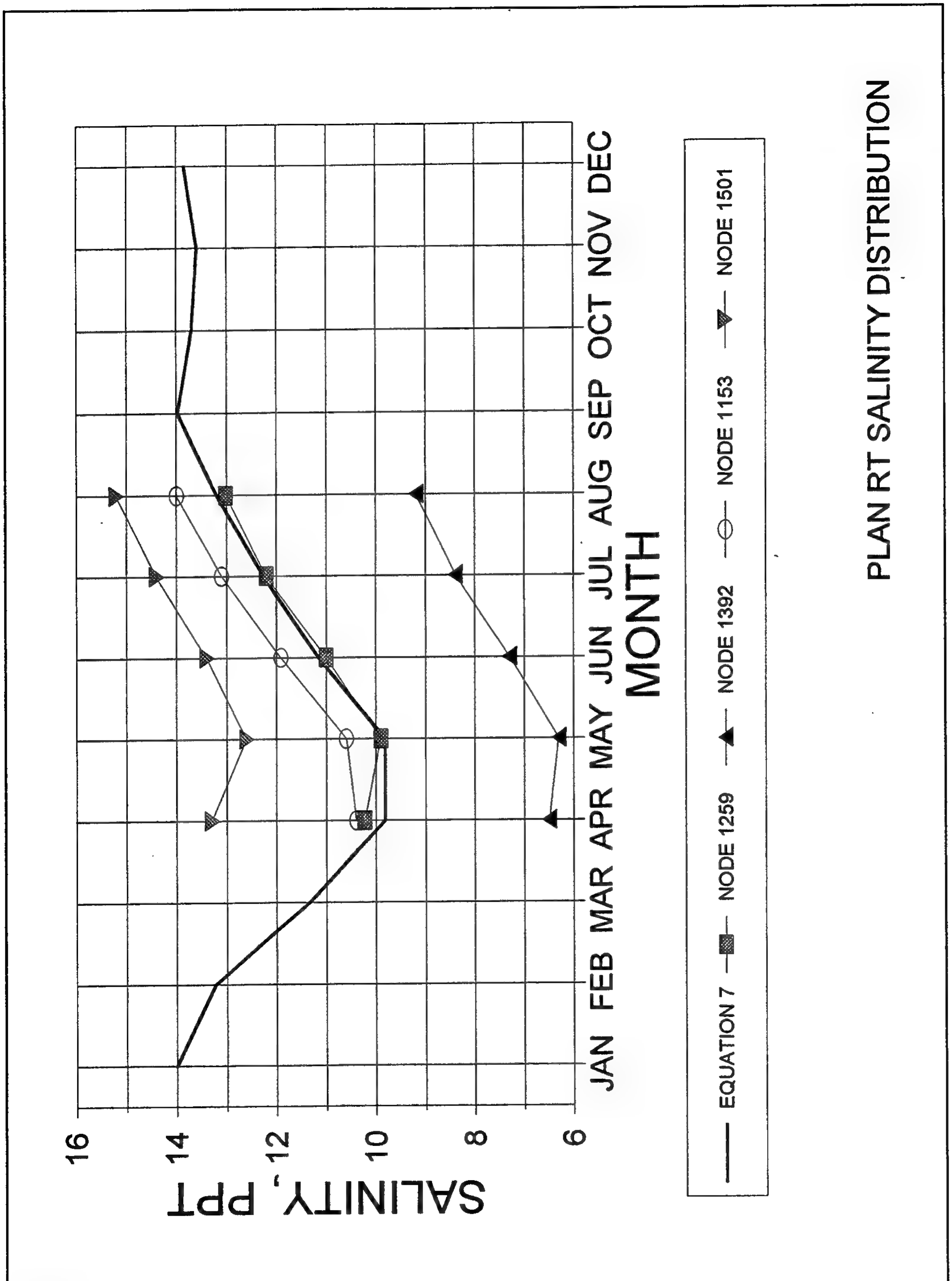
SALINITY, PPT
16
14
12
10
8
6
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
MONTH
EQUATION 7
NODE 1259
NODE 1392
NODE 1153
NODE 1501
PLAN RT SALINITY DISTRIBUTION

Plate 18

Appendix A
The Hydrodynamic Code

The geometric complexity of this estuary, with its navigation channel, multiple inlets, and many proposed disposal islands, requires a numerical model that relies upon an unstructured computational mesh. The code chosen is the Galerkin-based finite element model RMA10-WES, which is a U.S. Army Engineer Waterways Experiment Station (WES) adaptation of the RMA-10 code developed by King (1993). This code computes time-varying open- channel flow and salinity/temperature transport in 1, 2, and 3 dimensions. It invokes the hydrostatic pressure and mild slope assumption. Vertical turbulence is supplied using a Mellor-Yamada Level II (Mellor and Yamada 1982) *k*-ℓ approach modified for stratification by the method of Henderson-Sellers (1984). The salinity/density relationship is based upon Pritchard (1982).

The full three-dimensional equations are reduced to a set of two momentum equations, an integrated continuity equation, a convection-diffusion equation, and an equation of state. The simplification is a result of the hydrostatic pressure approximation.

$$\rho \frac{Du}{Dt} - \nabla \cdot \sigma_x + \frac{\partial P}{\partial x} - \Gamma_x = 0 \tag{A1}$$

$$\rho \frac{Dv}{Dt} - \nabla \cdot \sigma_y + \frac{\partial P}{\partial y} - \Gamma_y = 0 \tag{A2}$$

$$\frac{\partial h}{\partial t} + u_\zeta \frac{\partial \zeta}{\partial x} - u_a \frac{\partial a}{\partial x} + v_\zeta \frac{\partial \zeta}{\partial y} - v_a \frac{\partial a}{\partial y} + \int_a^\zeta \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz = 0 \tag{A3}$$

$$\frac{Ds}{Dt} - \frac{\partial}{\partial x}\left(D_x \frac{\partial s}{\partial x} \right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial s}{\partial y} \right) - \frac{\partial}{\partial z}\left(D_z \frac{\partial s}{\partial z} \right) \tag{A4}$$

$$\rho = F(s) \tag{A5}$$

Elevation-related terms are defined in Figure A1.

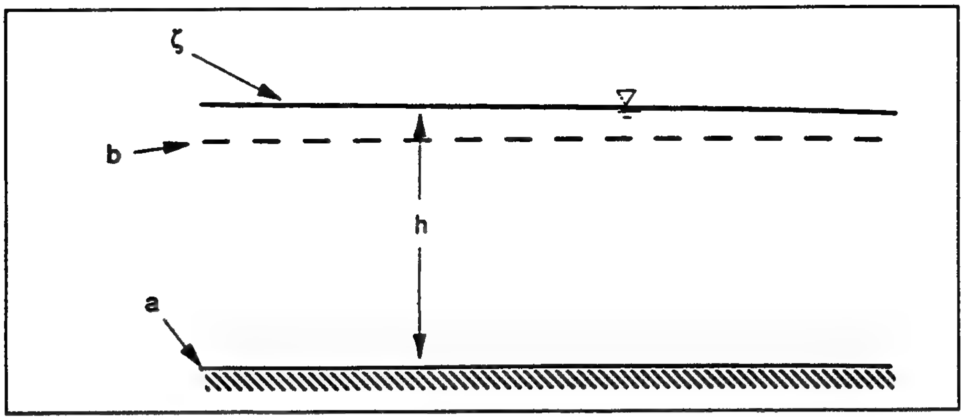

Figure A1. Definitions for elevation terms

where

$$\sigma_x = \begin{Bmatrix} E_{xx} \dfrac{\partial u}{\partial x} \\ E_{xy} \dfrac{\partial u}{\partial y} \\ E_{xz} \dfrac{\partial u}{\partial z} \end{Bmatrix} \quad ; \quad \sigma_y = \begin{Bmatrix} E_{yx} \dfrac{\partial v}{\partial x} \\ E_{yy} \dfrac{\partial v}{\partial y} \\ E_{yz} \dfrac{\partial v}{\partial z} \end{Bmatrix}$$

and

ρ = density
u,v,w = x,y,z velocity components
t = time
P = pressure

$$\Gamma_x = \rho\Omega v - \frac{\rho g u_a (u_a^2 + v_a^2)^{(1/2)}}{C^2} + \psi W^2 \cos(\Theta)$$

$$\Gamma_y = -\rho\Omega u - \frac{\rho g v_a (u_a^2 + v_a^2)^{(1/2)}}{C^2} + \psi W^2 \sin(\Theta)$$

$\Omega = 2\omega\sin(\phi)$
ω = rate of angular rotation of the earth
ϕ = local latitude
g = gravitational acceleration
C = Chezy or Manning friction formulation
ψ = a coefficient from Wu (1980)
W = wind speed
Θ = wind direction counterclockwise from easterly
h = depth
u_ζ, v_ζ = x,y velocity components at the water surface
ζ = water surface elevation

u_a, v_a = x,y velocity
a = bed elevation
s = salinity
D_x, D_y, D_z = diffusion coefficient for salt
E = eddy viscosity components

The continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{A6}$$

is solved as a second part of each solution step. Equation A6 is converted to an appropriate boundary value problem through differentiation with respect to z. After rearrangement it takes the form

$$\frac{\partial^2 w}{\partial z^2} = - \frac{\partial}{\partial z}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{A7}$$

subject to boundary conditions specified for the water surface and the bed:

$$w_\zeta = u_\zeta \frac{\partial \zeta}{\partial x} + v_\zeta \frac{\partial \zeta}{\partial y} + \frac{\partial h}{\partial t} \quad \text{at the water suface} \tag{A8}$$

and

$$w_a = u_a \frac{\partial a}{\partial x} + v_a \frac{\partial a}{\partial y} \quad \text{at the bed} \tag{A9}$$

Note that in these equations the values of u and v will be known at all locations from the previous part of the solution step. Values of w in this solution are used in the next iteration for $u,v,h,$ and s.

The geometric system varies with time; i.e., the water depth h varies during the simulation. In order to develop an Eulerian form for the solution, it is desirable to transform this system to one that can be described with a constant geometric structure. Early development of the model (King 1982) used a σ-transformation in which the bed and the water surface are transformed to constants. In a later analysis of this method, King (1985) pointed out that at locations where a sharp break in bottom profile occurs, the transformation is not unique and momentum in the component directions may not be correctly preserved. An alternative transformation that preserves the bottom profile as defined, but transforms the water surface to a constant elevation is now used (z^v transformation).

This transformation is defined by:

$$x^{\triangledown} = x \tag{A10}$$

$$y^{\triangledown} = y \tag{A11}$$

$$z^{\triangledown} = a + (z - a)\frac{(b - a)}{h} \tag{A12}$$

where b is the fixed vertical location to which the water surface will be transformed. Equations A1-A6 and A7-A9 then incorporate the transformation (A10-A12).

Another advantage of this transformation is that it produces $z^{\triangledown}$ = constant lines that are close to horizontal, i.e., z = constant lines. This results in less fictitious density-driven currents near bed profile breaks (Stelling and van Kester 1993). Since stratification-related phenomena are usually nearly horizontal, it is important that the transformation leave constant surfaces that are nearly horizonal. Considering the pressure gradient (due to the density gradient) in this transformation produces

$$\frac{\partial P}{\partial x} = \frac{\partial P}{\partial x^{\triangledown}} + \frac{\partial P}{\partial z^{\triangledown}}\frac{\partial z^{\triangledown}}{\partial x} \tag{A13}$$

In a strongly stratified stagnant system this pressure gradient should be zero. However, note that Equation A13 in the transformed system is dependent upon two terms (each of which could be large) to cancel each other. This could cause artificial currents due to truncation and roundoff error. A transformation in which $\partial z^{\triangledown}/\partial x \approx 0$, i.e., $z^{\triangledown} \approx z$, will reduce this problem. Figure A2 shows an example for a case similar to the Galveston project in which a 40-ft-deep channel passes through an 8-ft-deep bay. Here b is chosen to be an elevation of 0 and ζ is 2 ft. Near the break in the bed profile $\partial z^{\triangledown}/\partial x$ is fairly small, or $z^{\triangledown}$ surfaces are nearly horizontal. Contrast this with the σ transformation in Figure A3. The σ = constant surfaces are far from horizontal along the channel side slopes. The truncation and roundoff errors tend to drive fictitious currents that cause the denser salt water to leave the channel. The $z^{\triangledown}$ transformation results in

$$\frac{\partial z^{\triangledown}}{\partial x} = 0(\zeta - b) \tag{A14}$$

whereas the σ transformation is

$$\frac{\partial \sigma}{\partial x} = 0(h) \tag{A15}$$

which is much larger.

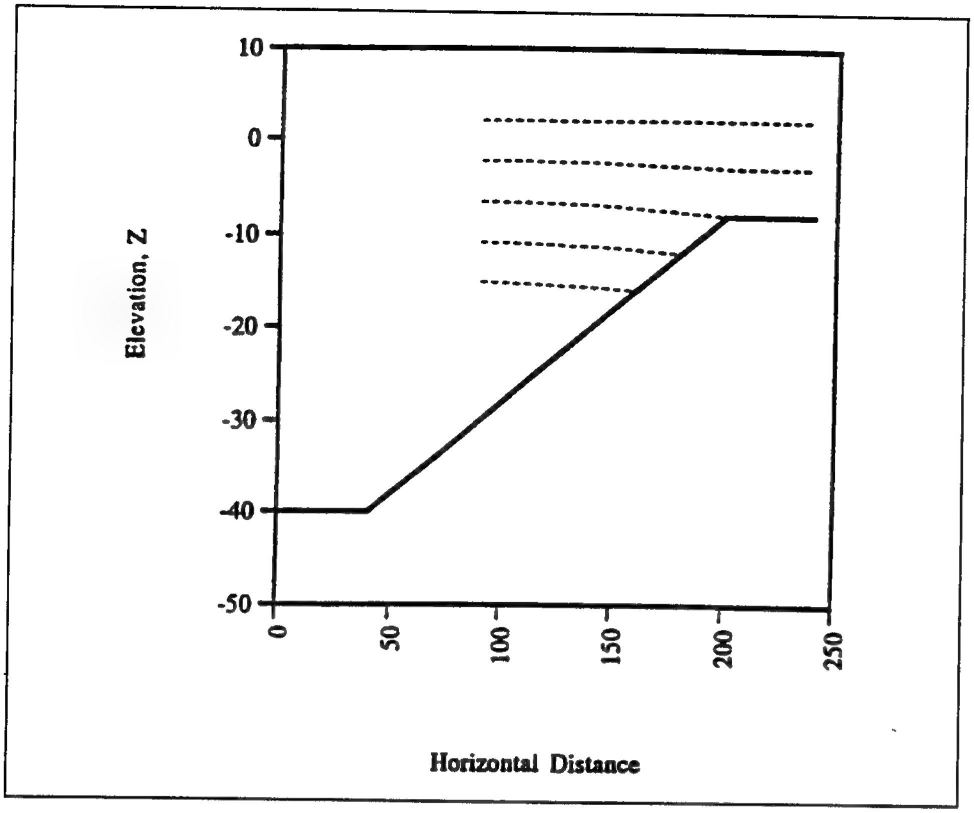

Figure A2. Lines of constant z^{∇} near a significant grade change

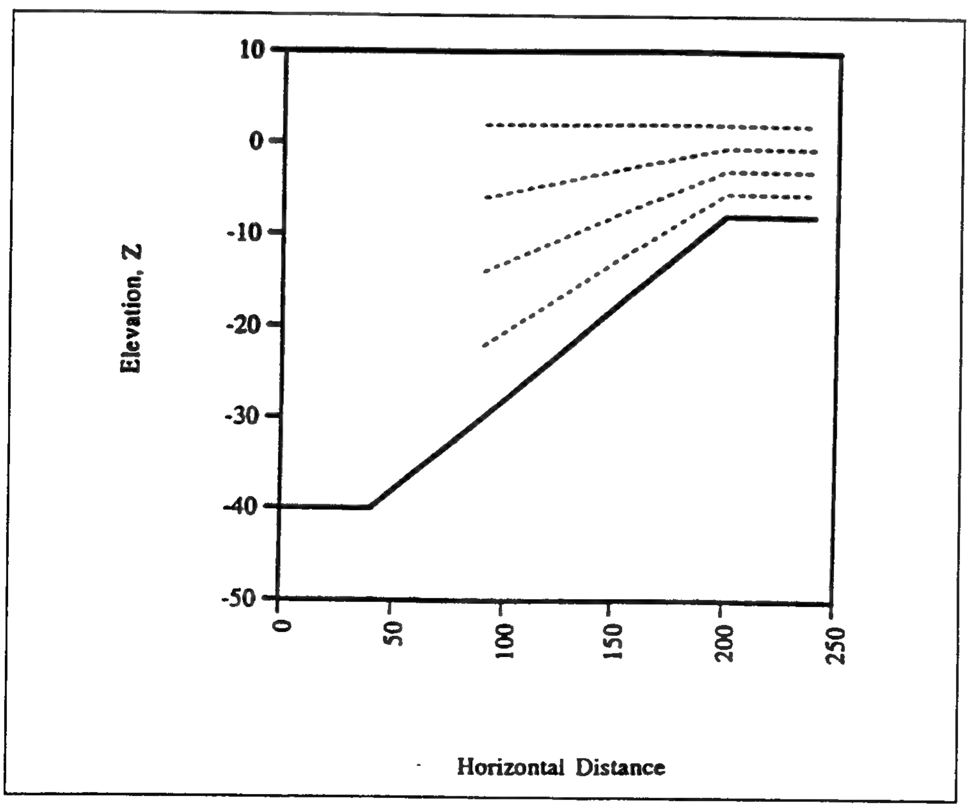

Figure A3. Lines of constant σ near a significant grade change

The Galerkin finite element approximation of Equations A1-A4 and A7 uses a quadratic approximation for u,v,w, and s and linear for h and P. The nonlinearity is addressed by Newton-Raphson iteration at each time-step. Generally the iteration process is split into calculation of Equations A1-A3, then A7, followed by A4. This sequence is repeated until sufficient convergence is reached.

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William H. McAnally, R. C. Berger

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13. ABSTRACT *(Maximum 200 words)*

Numerical model experiments were performed to predict salinity changes that will occur in the Lake Pontchartrain basin estuary, Louisiana and Mississippi, as a result of proposed Mississippi River freshwater diversions through the Bonnet Carré spillway near New Orleans. One purpose of the diversion is to reduce salinities in the Biloxi Marshes by 2 to 8 parts per thousand (ppt) in order to improve oyster productivity. A range of monthly salinities has been identified as the desired product of the project. Those salinities, called the Chatry salinities in this report, consist of a narrow band of "optimum" salinities and a somewhat wider band of "range limits."

A time-varying, three-dimensional numerical model of the estuary was constructed using the U.S. Army Corps of Engineers TABS-MD modeling system. The modeled area included Lakes Maurepas, Pontchartrain, and Borgne, Biloxi Marshes, and a portion of Chandeleur Sound plus connecting waterways of Mississippi River-Gulf Outlet (MRGO), Inner Harbor Navigation Canal, Gulf Intracoastal Waterway, Chef Menteur, and The Rigolets. All major tributary freshwater flows were simulated, as were tides at the Gulf of Mexico boundary and winds. The model computed instantaneous water levels and current velocities and salinities in three spatial dimensions throughout the area modeled. The model was verified to satisfactory reproduce hydrodynamic behavior observed in the natural system in 1982 and 1994.

(Continued)

14. SUBJECT TERMS

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Diversion	Numerical model
Hydrodynamics	Salinity

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13. ABSTRACT (Concluded).

Four conditions were modeled for April through August of a typical year: a Base condition with no diversion, Plan RT with freshwater diversions up to 20,000 cfs, Plan MBP5 with freshwater diversions up to 8,500 cfs, and Plan LBC1, with no freshwater diversions but with the connections between the MRGO and Lake Borgne closed.

The numerical model results were used to construct a simple regression equation that relates Biloxi Marsh salinities at a point to freshwater flows from the natural tributaries plus the diversions. The equation was then used to develop other diversion schedules that offered various salinity reduction scenarios.

The following conclusions and recommendations are drawn from the work:

a. The estuary responds very slowly to changes in freshwater inflow to Lake Pontchartrain. For example, in the Biloxi Marshes salinity effects are noticeable within 30 days of a change in flow, but the peak effect occurs at about 60 days, and a noticeable residual effect remains at 120 days.

b. The MRGO is a significant contributor to the salinity regime in the Lake Pontchartrain to Biloxi Marshes area, primarily via MRGO connections to Lake Borgne.

c. A Bonnet Carré structure discharge capacity of about 30,000 cfs is required to achieve the desired spring salinity of about 6 ppt about every other year at Line 2, a location in the Biloxi Marshes identified as the target location in the General Design Memorandum (GDM). However, any year in which that low salinity is achieved (either by diversion or natural freshening) will be fresher than desired in the subsequent 2 months because of the slow response time of the system.

d. The plans considered here will reduce salinities at Line 2 in the Biloxi Marshes for a typical year (50 percent exceedance flows). Specifically, compared to the Base, or no diversion, condition, the plans had the following effects on salinities at about the center of Line 2:

(1) Plan RT (up to 20,000 cfs) reduced salinities up to 4.2 ppt during April-August. It reduced salinities to Chatry optimum values or less for 10 months out of 12.

(2) Plan MBP5 (up to 8,500 cfs) reduced salinities up to 3.4 ppt during April-August. It reduced salinities to Chatry optimum values or less for 9 months out of 12.

(3) Plan LBC1 (closure of Lake Borgne-MRGO connections) reduced salinities up to about 2 ppt during April-August.

e. Other potential diversion schedules can be devised and salinity reduction approximated by the simple equation developed in this report without additional model experimentation in order to balance achievement of salinity goals with other criteria. However, any plan devised by that method should be subjected to model experimentation before design is complete and before an operational plan is designed.

f. Control of salt flux up MRGO and through the outlets can contribute significantly to achieving Biloxi Marsh salinity goals. Possible control methods are discussed in Chapter 5 of this report. By extension, it may be possible to combine MRGO salt contributions with smaller diversions (e.g., MBPJ) to approach target salinities at Line 2.

g. The basin response conclusions in item *d* imply that a Bonnet Carré diversion schedule must be statistically based. Before construction of a project, the plans reported here must be replaced with a diversion operational plan that takes into account antecedent conditions and a stochastic forecast of future tributary inflows. Such an operational plan will produce some years fresher than desired and some years saltier than desired, as described in the GDM. Chapter 5 of this report suggests an approach for developing such an operational plan.